HEAD OVER HEELS: THE EFFECTS OF THREE HEEL HEIGHTS ON POSTURAL AND ACOUSTICAL MEASURES OF UNIVERSITY FEMALE VOICE MAJORS, AND MEASURED RELATIONSHIPS BETWEEN HEEL HEIGHT, PITCH, VOWEL, BEHAVIOR, HEAD POSITION, JAW OPENING, AND DB SPL

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Abstract

The purpose of this study was (a) to determine the effects, if any, of 3 simulated heel height conditions (0.0 in., 1.5 in., 3.0 in.) on postural (head position, jaw opening) and acoustical (LTAS, dB SPL) measures of university female voice majors (*N* = 35) in 2 conditions (silence, singing sustained [ɑ] and [i] vowels on each pitch of a 2-octave A-major scale [A3-A5]), and then to (b) assess selected relationships between heel height behavior conditions, postural data, and acoustical data.

Primary findings included significant main effects for heel height, pitch, vowel, behavior, and formant location conditions on participants' postural and acoustical data. As heel height increased, participants significantly (a) decreased head position angle 1 and angle 2, (b) decreased jaw opening, (c) decreased LTAS mean signal energy, and (d) increased amplitude (dB SPL). As pitch ascended, participants, on average, significantly (a) increased head position angle 1 and angle 2, (b) increased jaw opening, and (c) increased amplitude (dB SPL). When singing the open vowel of [ɑ] compared to the closed vowel of [i], participants significantly (a) increased head position angle 1 and angle 2, (b) increased jaw opening, and (c) increased amplitude (dB SPL). From silent to singing behaviors, participants significantly (a) increased head position angle 1 and angle 2, and (b) increased jaw opening. Participants significantly increased head position angle 1, head position angle 2, and jaw opening when singing pitches above the point where the fundamental frequency (F0) would equal or exceed the first format frequency (F1) of the low pitch of A3.

Data analyses yielded multiple significant interactions between independent variables and indicated significant, moderate to strong, positive relationships between (a) pitch and dB SPL, (b) pitch and jaw opening, (c) jaw opening and behavior, (d) jaw opening and head position angle 1, and (e) jaw opening and dB SPL, and significant, moderate, negative correlations between (a) jaw opening and vowel, and (b) heel height and head position angle 1.

Results were discussed in terms of general outcomes, considerations for vocal music education and voice research, limitations of the study, and suggestions for future investigations.

Keywords: heel height, pitch, vowel, head position, jaw opening, formant tuning

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CHAPTER ONE

Introduction

Archaeological evidence indicates that human beings began using footwear at least as early as the Stone Age (Trinkaus, 2005). For example, Spanish cave drawings from approximately 15,000 years ago depict humans with animal furs wrapped around their feet. The oldest existing human footwear, found in a cave in Armenia, dates back to approximately 3627-3377 BC (Pinhasi et al., 2010).

High-heeled footwear exists since at least 3500 BC ("Dangerous Elegance," 2008). Historical evidence indicates that high heels first appeared on the feet of men. Egyptian butchers would wear high heels to stay above the bloodied butcher shop floor (Kurup, Clark, & Dega, 2012). Paintings show Persian male warriors sporting high heels as they rode on horseback and used the area between the shoe sole and heel to help them stand up on stirrups and shoot arrows (Kremer, 2013) (see Figure 1).

Figure 1. The Vision of Saint Eustace (1438-1442) by Pisanello. The painting features a male rider on horseback wearing heels.

Historians describe Venitian women wearing chopines during the 15th, 16th, and 17th centuries ("Chopines – Platform Heels Renaissance Style," 2010). Featuring wood or cork platforms, these shoes apparently make it difficult to walk, but protect dresses from street dirt and mud (see Figure 2). The higher the height of the chopine, the more superior the social class and wealth of a woman.

Figure 2. Reconstruction of a 16th century Venitian chopine. The shoe is on display in the Shoe Museum Lausanne in Lausanne, Switzerland.

Wade (2013) suggests that aristocratic men in Europe also wore high-heeled shoes as a symbol of status. Apparently, townspeople would assume that anyone wearing such impractical footwear did not have to work for a living. Figure 3 portrays King Louis XIV wearing red heels. Another article describes how King Louis XIV ordered that no one could wear high heels taller than his and that only nobility could wear red heels ("Dangerous Elegance," 2008).

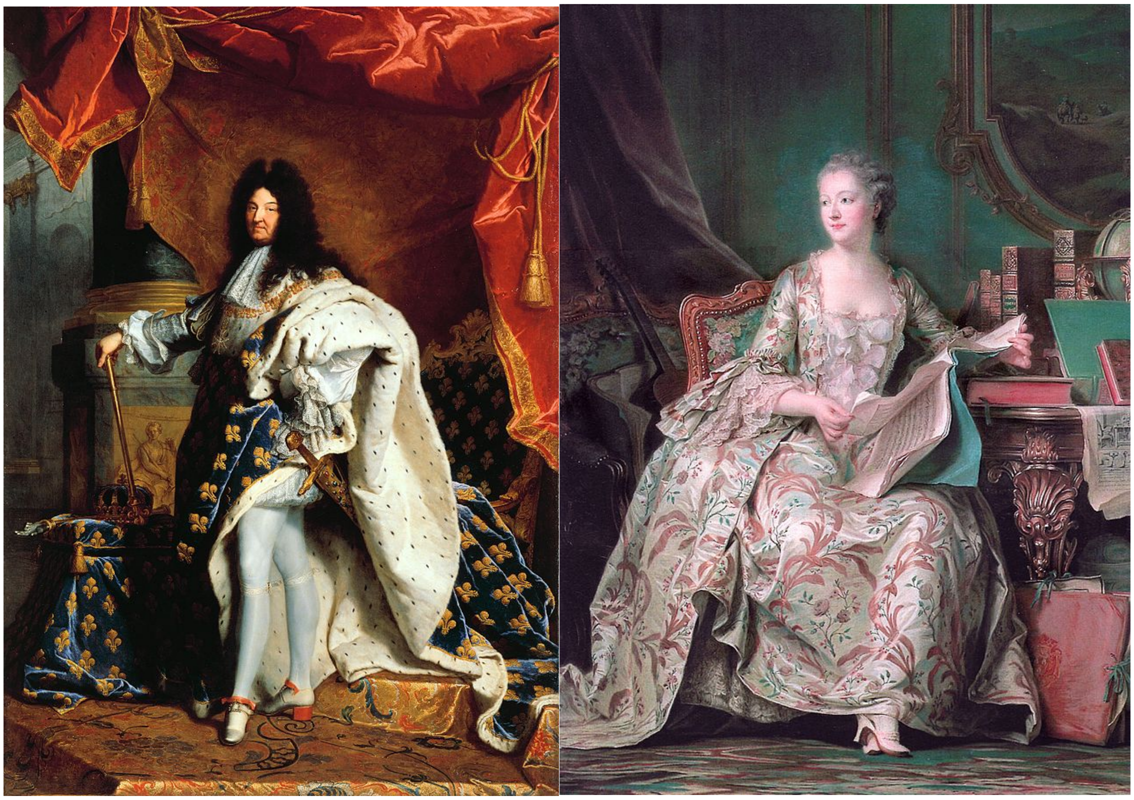

Figure 3. Portrait of Louis XIV in 1701 by Hyacinthe Rigaud and portrait of Madame de Pompadour (1721-1764) at the Paris Salon in 1755 by Maurice Quentin de La Tour.

Figure 3 also depicts King Louis XIV's mistress, Madame de Pompadour (also known as Jeanne Antoinette Poisson, Marquise de Pompadour), wearing a similar type of heel. This style of shoe, featuring a thick heel with a concave curve, still exists today under the style label of "Louis heels" or "Pompadour heels" ("Dangerous Elegance," 2008).

During the 1630s, women began to wear high-heeled shoes in an effort to appear more masculine (Wade, 2013). As the wearing of high heels filters down to the lower classes, aristocrats respond by increasing the height of their heels and designating thick heels for men and thin heels for women (Wade, 2013). Wade suggests that men eventually abandoned the wearing of high heels due to an increasing association between high heels and women.

During the Enlightenment period (1650s – 1780s), society focuses on reason and practicality, and the popularity of high heels decline with both sexes (Kremer, 2013). Napoleon even banishes high heels to establish equality ("Dangerous Elegance," 2008). For years, the slipper and flat shoe gain popularity. However, the mid-nineteenth century witnesses a resurgence of high-heeled footwear among women, and the invention of photography abets French pornography postcards that picture nude models wearing high heels (Kremer, 2013) (see Figure 4). For the remainder of the nineteenth century, high heels continue to go in and out of fashion.

Figure 4. La Grande Epidémie Pornographie by C. E. Jensen, a 19th century French engraver. This illustration appears in *Karikatur Album II*, page 332.

Although a primary purpose of footwear is to protect the feet, the design of fashion footwear has changed from soft, flexible moccasins to the hard, high-heeled stilettos prevalent in Western society today (Thompson & Coughlin, 1994). Interestingly, women in non-shoe wearing civilizations do not exhibit many of the foot problems that plague women in shoe wearing societies do (e.g., Hoffman, 1905; James, 1939; Sim-Fook & Hodgson, 1958).

An American Podiatric Medical Association (APMA) survey of adults from the general population ($N = 1000$) indicates that of the 49% of self-reported, female, high heel wearers, 71% admit to wearing high heels that hurt their feet (Day, 2014). Thompson and Coughlin (1994) estimate the yearly American healthcare cost attributed to high heels exceeds 3 billion dollars. Women even have the option of having a doctor inject Botox into the balls of the feet or perform a surgery to trim their toe bones in order to wear high heels longer (e.g., Sherr, 2006).

One might wonder why women would wear high heels that induce pain and encourage high doctor bills. Some researchers believe women endure the pain of high heels because shoes can be used to evaluate them in terms of age, sex, income, and attachment anxiety (e.g., Gillath, Bahns, Ge, & Crandall, 2012). Rossi (1993) asserts that women wear high heels because high heels affect how they are perceived by the male sex and assist them in securing a potential mate. It appears that some women feel that high heels oppress them, while others feel high heels empower them (e.g., Coffey, 2009). Some women believe high heels boost their confidence (e.g., Lepore 2012). However, Freeman (2013) remarks, “For me, high heels are just fancy foot binding with a three-figure price tag” (para. 8).

Debates on Heel Height for Singing

A recent article details the importance of shoes in opera. Plotkin (2015) writes that the famous opera singer, Beverly Sills, felt that when she sang opera roles, her shoes influenced her characterization and movement. Sills selected her own shoes rather than wearing the ones picked by the costume designer. Plotkin describes another famous singer who chose flats and less than stunning Birkenstock shoes because they gave her the support and comfort she needed to sing. Plotkin quotes the famous dramatic soprano Birgit Nilsson, who remarked that her shoes were the secret to her success in singing long Wagner roles (Plotkin, 2015).

Willis (2015), in a review of the footwear worn by both male and female contestants during the BBC Cardiff Singer of the World competition, praises the male singers by saying, “the men have excelled themselves. More patent shoes, traditional with tails, than ever before. But more importantly, CLEAN. So many singers forget that, for the stalls audience, shoes are at eye level” (para. 2). Willis comments that for petite singers, high heels offers them a presence on stage and for all singers, a well-matched shoe gives assurance.

Female singers must make daily choices about footwear in their everyday lives, but also while singing an audition or performance. Shoes can be a hot topic of debate among performers wanting to look and sound impressive. One singer finds “the thought of showing up for an A house audition for a leading lady role in Payless pumps amusing,” and says, “you cannot go into an audition wearing grandma pumps and expect to get the job” (Milin, 2015). Another singer believes that the shoes she owns, although cheap, are the only heels she has ever had that do not make her "feet or back hurt or mess with breath support" (Weaver, 2015).

Singing voice teachers appear to have mixed opinions about the appropriate shoe heel height for auditions or performances. Eichhorn-Young (2010), for example, recommends wearing high-heeled shoes for auditions and performances. She says, "Flats make you look like you have stove pipes for legs and generally make you stand like a duck," (lines 16-17). However, del Santo (2005) comments, "Ladies should wear a pair of pumps with a heel of comfortable height. (Remember that posture affects your voice!) Avoid open-toed sandals or boots with thick heavy heels" (lines 72-74).

Some laryngologists view high heels as a cause of tension in the body that could affect singing. Jahn (2014), for instance, advises singers to avoid heels and comments that "from the vocal point of view, half-heels or flats are better" (lines 36-37). Wilson Arboleda, and Frederick (2008) argue that high heels negatively impact postural alignment, as can heavy costuming, corsets, raked stages, and character requirements.

Posture and Singing

Voice teachers typically address singer posture as one of the fundamental elements of singing. Lennon (1985) remarks that all beginning vocal instruction should start with, "first establishing a balanced structural alignment for the body-instrument" (p. 49). McCoy (2010) lists posture first in his article on building a foundation for singing. Some researchers even recommend physical therapy as a means to optimize posture for student classical singers (Staes et al., 2011).

A Google search of the term "singing posture" yields approximately 779,000 results. McKinney (1994) places his chapter on posture before chapters on breathing and support, phonation, registration, voice classification, resonation, and articulation. McKinney argues, “No competent athlete would attempt to perform his particular skill without first engaging in a series of bending, stretching, and shaking-out exercises” (p. 35). McKinney describes the elements of good posture including the feet, legs, knees, hips and buttocks, abdomen, back, chest, shoulders, arms and hands, and the head. Although McKinney comments that too much emphasis on posture could lead to tension and rigidity, he believes good posture and good singing are interrelated.

Vernard (1967) also warns that posture can be overemphasized because teachers may feel posture is one area of vocal pedagogy where they can be assured of their instruction, but “it soon becomes dull to the student and takes the fun out of singing” (p. 19). However, Vennard reminds students that the great opera singers probably focused on posture early in their training.

Head Position and Jaw Opening with the General Population

The medical field considers head position to be an important element in maintaining cervical health. Children, teens, and adults exhibit “text neck” from using smartphones and tablets with a forward head position (Wilson, 2012). A forward head position, or the protrusion of the head on the sagittal plane, places the head anterior to the trunk and constitutes one of the most prevalent abnormalities associated with neck pain (Bryden & Fitzgerald, 2001). A person with a forward head position of 60 degrees adds 60 pounds of force to the cervical spine (Hansraj, 2014). Persons using computers are also at risk for increased cervical spine loading (Bonney & Corlett, 2002).

Jaw disorders also affect the general population. The National Institute of Dental Research and Craniofacial Research states that temporomandibular joint and muscle disorders constitute the most common cause of facial pain (Facial Pain, n.d.).

Singers might wish to consider carefully any information on head or neck posture because the voice instrument resides in the head and neck. Similarly, because singers may use the mandible in order to pronounce words or open the mouth to sing, information about jaw opening with the general population and with singers merits attention.

Debates on Optimal Head Position and Jaw Opening for Singing

Feldenkreis, Alexander, Pilates, and other techniques are common methods for singers seeking freedom in movement, balance, support, flexibility, and coordination (Gloss, 2009; Fisher, 1988; Robinson, Fisher, Knox, & Thomson, 2002; Feldenkrais, 1972). The Alexander Technique Brussels website states that the erect posture and forward head position of F. M. Alexander ultimately contributed to his vocal problems (Vettas, n.d.). Some Alexander method instructors teach that the head must find balance on top of the spine (e.g., Hudson, 2002). Vall, a certified instructor of Alexander technique, comments that the head should also be able to move freely (Vall, 2010).

Voice professionals offer contrasting opinions on the most optimal head position for singing. Rubin (2004) writes that stage directions, an opera house with high balconies, raked stages, or a singer's height could potentially cause a performer to lift the head up, which he claims puts increasing pressures on the joints between the vertebrae. Davids and LaTour (2012) recommend that singers tilt the head and chin down slightly to counteract the tendency to raise the chin as pitch ascends, but comment that if the chin is lowered too much, jaw opening becomes difficult. On the other hand, Austin (2012) discusses the problems of singers who tilt their heads down to simulate the voices of more mature singers. Austin maintains that a lowered head position will prevent a singer from achieving higher pitches and lead to premature fatigue.

Heman-Ackah (2005) states that a lifted chin or neck creates a bend in the pharyngeal area, which narrows the resonance at the region of the tongue base. She advises singers to keep the head in a neutral position, which enhances resonance and projection. Miller (2004) comments that the "back of the neck should feel long and the front of the neck short, not the other way around" (p. 38). When asked if the head could be held too low, Miller responds that the head should not be too high or too low. He further warns that the head must not elevate for ascending pitch or lower for descending pitch.

Austin (2013) argues that an elevated head position does not have to correspond with an elevated laryngeal position. He gives the example of Birgit Nilsson who sang with an elevated head position and exhibited beautiful, soaring high notes. Austin believes that lifting the head can be an extremely important pedagogic tool as it helps students release tongue, jaw, and throat tension. He also gives examples of singer head positions that change as a result of jaw opening alterations, dependent on pitch and dynamics. He describes how Leontyne Price opens the jaw to a greater degree as she ascends a scale. Austin also argues that head position and jaw opening can change with musical style. He points, for instance, to Barbara Streisand, who employs a large mouth opening to belt, in contrast to opera singer Luciano Pavarotti, who did not open the mouth as much. Austin contends that head position and jaw opening can be essential to optimizing vocal function.

Historical vocal pedagogy offers varying opinions on the optimal jaw opening for singing. Fields (1947) lists the wide-variety of opinions from early 20th century pedagogues concerning optimal jaw opening for singing. White (as cited in Fields, 1947), comments “The high notes require only a small mouth opening” (p. 115). Marchesi (as cited in Fields, 1947), on the other hand, argues “The higher the tone, the lower the jaw must drop” (p. 115). Owsley (as cited in Fields, 1947) quotes Lamperti who says “He who moves the mouth will never become a singer” (p. 115). However, Wilson (as cited in Fields, 1947) says, “Failure to open the mouth will result in rigidity” (p. 115). Hill (as cited in Fields, 1947) also warns singers “Do not tilt the head back when dropping the jaw” (p. 115).

Coffin (1987) advises singers to free the jaw by showing the lower teeth and letting the lower jaw hang. He remarks, “Drop the chin for passaggio and high notes, never the jaw” (p. 30). Coffin also advises singers to close mouth opening when descending in pitch, which he believes gives the lower notes higher overtones.

Jones (n.d.) advises singers to let the jaw hang slightly down and back, but never forward. He argues that many singers open the mouth too much and the jaw protrudes forward, which makes legato singing impossible. He recommends using a gentle chew function to help release the jaw for healthy singing and speaking.

Need for the Study

Vocal pedagogy literature offers various anecdotal and conflicting viewpoints concerning ideal (a) heel height, (b) head position, and (c) jaw opening for singers.

Although various published research studies examine some of these variables, either singly or in dyads, no empirical study to date has examined simultaneously all of these variables with female singers.

Moreover, some research in non-singing contexts indicates moderate to strong relationships between head position, jaw opening, and the dimensions of the vocal tract. Some research in singing contexts indicates that jaw opening changes with pitch and vowel, alters the first formant frequency, and assists in formant tuning for female voices, allowing them to increase dB SPL without increased vocal effort.

Only two studies to date (Rollings, 2013, 2014a) assess the effects of shoe heel heights on female singers. Results from these studies suggest that from barefoot to high heel conditions, female singers lower head position and evidence significant differences in LTAS and the formant frequencies of low pitches.

Therefore, one might reasonably hypothesize that if variations in heel height could elicit alterations in singer head position, then modification of singer head position, in turn, could prompt changes in jaw opening, timbre (specifically the ability to formant tune in higher frequencies), and dB SPL. A study that explores this possibility with female singers could be of considerable interest to singers, singing teachers, and researchers.

Purpose of the Study

The purpose of this study was (a) to determine the effects, if any, of three simulated heel height conditions (0.0 in., 1.5 in., 3.0 in.) on postural (head position, jaw opening) and acoustical (LTAS, dB SPL) measures of university female voice majors (*N* = 35) in two conditions (silence, singing sustained [ɑ] and [i] vowels on each pitch of a two-octave A-major scale [A3-A5]), and then to (b) assess selected relationships between heel height behavior conditions, postural data, and acoustical data.

Research Questions

The following research questions guided this investigation (see Appendix A for a complete list of research and sub-research questions).

1. Are there statistically significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (b) two behavior conditions (silent, singing), (c) two vowel conditions ([ɑ], [i]), and (d) three pitch conditions (low [A3], medium [A4], high [A5])?
2. Are there statistically significant differences among LTAS data (0 – 10 kHz) acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), and (b) two vowel conditions ([ɑ], [i])?
3. Are there statistically significant differences among dB SPL (0 – 10 kHz) measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (b) two vowel conditions ([ɑ], [i]), and (c) three pitch conditions (low [A3], medium [A4], high [A5])?
4. Are there statistically significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from (a) two vowel conditions ([ɑ], [i]) and (b) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), after disaggregating and averaging data for

each dependent variable into levels of $\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0})?

5. Are there statistically significant relationships between (a) two measures of participant head position (HP 1, HP 2), (b) one measure of participant jaw opening (JO), (c) dB SPL, (d) three heel conditions (0.0 in., 1.5 in., 3.0 in.), (e) two vowel conditions ([ɑ], [i]), (f) 15 pitch conditions (A3-A5), and (g) two behavior conditions (silent, singing)?

Definitions

Formant frequency. Formant frequencies are resonances determined by the shape and length of the vocal tract, which changes due to the positioning of the larynx, tongue, lips, jaw, and pharynx. A formant will boost the amplitude of nearby harmonics in the sound spectrum. If a harmonic is not close to a formant, it may be attenuated. The first five formants determine vocal timbre (F1-F5) and formants one and two typically correspond with vowel intelligibility.

Fundamental frequency (F_0). Fundamental frequency corresponds with the rate of vocal fold vibration (Hz) and constitutes the lowest frequency of a waveform.

Gait. Gait describes the manner of walking.

Head extension and flexion. Head extension and flexion are anatomical terms of motion. Head extension occurs when a person moves the head superiorly and head flexion occurs when a person moves the head inferiorly (see Figure 5).

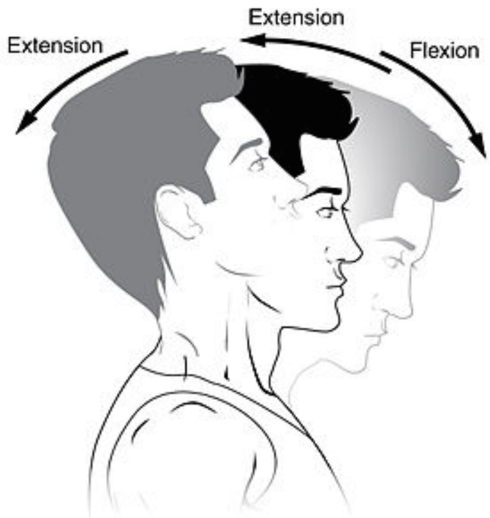

Figure 5. Head extension and flexion.

Knee flexion and extension. Knee flexion and extension are anatomical terms of motion. Knee flexion occurs when a person exhibits a greater bending of the knees. Knee extension occurs when a person exhibits a greater straightening of the knees.

Long-term average spectra (LTAS). Long-term average spectra data consist of the mean amplitude of each harmonic of a complex sound across a given time period. Thus, they can be useful for identifying persisting spectral events.

Lumbar lordosis. Lumbar lordosis refers to the inward curve of the lumbar spine. An increase in lumbar lordosis represents a greater amount of curvature in this region, while a decrease in lumbar lordosis signifies a more flattened curve.

Resonance tuning (Formant tuning). Opera singers, especially soprani, use resonance tuning in order to increase vocal efficiency and overall amplitude while singing high pitches. When the fundamental frequency of a given pitch exceeds the first formant frequency of the vocal tract, female singers raise the first formant frequency to equal or exceed the fundamental frequency, which consequently boosts the amplitude of the fundamental or first harmonic frequency.

Sound pressure level (dB SPL). Sound pressure level is a logarithmic measure of sound pressure (dB). Titze (2000) gives the formula for SPL measurement: $SPL=20\log_{10}P/P_0 dB$, where P_0 designates the standard reference air pressure.

CHAPTER TWO

Review of Literature

This chapter reviews empirical studies completed to date concerning heel height, head position, and jaw opening with general and singing populations. These studies will be reviewed according to topic and the primary population addressed (general public, speakers, singers).

High Heels: Non-Singing Contexts

Researchers have studied extensively the effects of high-heeled shoes in non-singing contexts on participants drawn from the general population. High-heeled shoe research with the general population has indicated five primary groups of potential effects: (a) pain and injuries, (b) gait, (c) mean center of gravity, (d) muscular compensation, and (e) posture.

Pain and injuries. Various studies have found that wearing high-heeled shoes contributed to various types of pain and injuries, including (a) foot deformity and increased arch height (e.g., Frey, Thompson, Smith, Sanders, & Horstman, 1993; Ricci & Karpovich, 1964), (b) hallux valgus (e.g., Menz & Morris, 2005; Frey et al., 1993; Yu et al., 2008), (c) osteoarthritis, knee pain, and increased knee torque (e.g., Kerrigan, Todd, & Riley, 1998; Kerrigan et al., 2005), (d) Achilles tendonitis, hammer toes, bunions, bunionettes, corns, plantar callouses (e.g., Sim-Fook & Hodgson, 1958; Menz & Morris, 2005), (e) back pain due to increased ground reaction forces (e.g., Bird & Payne, 1999; Lee, Jeong, & Freivalds, 2001; Ebbeling, Hamill, & Crussmeyer, 1994), and (f) musculoskeletal pain (e.g., Esenyel, Walsh, Walden, & Gitter, 2003).

Frey et al. (1993) studied a sample of women ($N = 356$), ages 20 to 60. Seventy-five percent of participants represented women being treated by an orthopedic doctor for all types of complaints. Results indicated that out of all participants, including the patients of the orthopedic doctor, 75% had not had their feet measured in over five years. A majority of women admitted to having some foot pain (80%) or one or more foot deformities (76%). The researchers determined that 88% of the participants wore shoes that were too small for their feet by an average of 1.2 cm.

Gait. A body of studies have examined the potential effects of wearing high-heeled shoes on human gait. Among the major findings: (a) altered lower extremity joint kinetic function (e.g., Esenyel et al., 2003), (b) alteration of normal gait patterns including a decrease in step length and stride length (e.g., Merrifield, 1971; Adrian & Karpovitch, 1966; Murray, Kory, & Sepic, 1970), (c) muscle fatigue (e.g., Gefen, Megido-Ravid, Itzchak, & Arcan, 2002; Mika A., Oleksy, Mika, P., Marchewka, & Clark, 2012), (d) increased activity in the cervical paraspinal muscle leading to chronic neck fatigue (e.g., Mika A., Oleksy, Mikolajczyk, Marchewka, & Mika P., 2011), (e) decreased walking speed and mobility (e.g., Murray et al., 1970), and (f) unnatural plantar pressure distribution patterns (e.g., Snow & Williams 1994).

Women wearing high heels while walking exhibited an increased likelihood of an ankle sprain or break (e.g., Nieto & Nahigian, 1975; Ebbeling et al.,1994) and increased probability of a slip or fall (Manning & Jones, 1995; Blanchette, Brault, & Powers, 2011). Mathews and Wooten (1963) and Ebbeling et al. (1994) found that participants used a significantly greater amount of oxygen and exhibited an increased heart rate while walking in high heel conditions compared to barefoot conditions.

Mean center of gravity. The mean center of gravity in a human body is the theoretical point at which body mass is most concentrated. The mean center of gravity changes with each new body positioning and is essential in the maintenance of body equilibrium and balance. A person has a greater ability to balance the body with a lower mean center of gravity compared to a higher mean center of gravity. If the line of gravity falls outside the base of support (the feet and legs), a physiological reaction is necessary in order for the body to stay balanced (Abdul Khadir, Lowe, Ritchie, Buxton, & Lowe, n.d.).

Several studies (e.g., Corrigan, Moore, & Stephens, 1993; Shimizu & Andrew, 1999) have reported alterations in the mean center of gravity, primarily a forward and medial pressure increase, with standing participants wearing high heels. Gerber et al. (2012) studied experienced women heel wearers (*N* = 53) standing on a force plate in (a) barefoot and high heel conditions and (b) eyes opened and eyes closed conditions. The researchers found significant differences in tests of static balance between comparisons of all conditions. Results indicated that high heels significantly altered the static balance of participants and produced an oscillation of the center of gravity. According to Mika et al. (2011), the ability to compensate for changes in the mean center of gravity decreased with age.

Muscular compensation. The erector spinae defines a group of back muscles that originate in the sacrum and spread vertically up the length of the spine. The erector spinae includes three individual muscles: (a) iliocostalis, (b) longissimus, and (c) spinalis. During erector spinae extension, the spine adjusts with an anterior head movement and a posterior chest movement (e.g., a person bending over to touch the floor). When the erector spinae flexes, the head moves posteriorly while the chest moves anteriorly (e.g., straightening the spine) (Erector Spinae, n.d.) (see Figure 6).

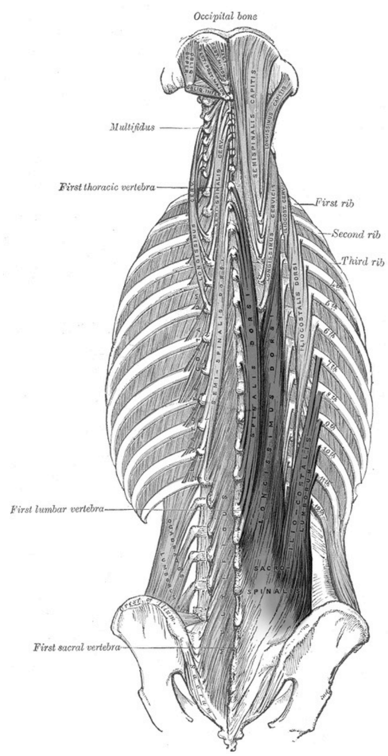

Figure 6. Location of the erector spinae muscle group with three muscles darkened (iliocostalis, longissimus, and spinalis).

Lee et al. (2001) examined participants ($N = 5$) standing and walking in three heel height conditions. The researchers found an increase in the height of the mean center of gravity, which corresponded to an increase in erector spinae muscle activity. The researchers reasoned that participants increased the muscular activity in the erector spinae in order to compensate for the irregular posture and the sensation of falling forward produced by high heels. Others studies have confirmed that when participants wore high heels, they also decreased the degree of lumbar lordosis (the inward curve of the lumbar spine), which consequently contracted the erector spinae. A contraction of the erector spinae produced concurrently a contraction of the abdominal muscles (e.g., Opila, Wagner, Schiowitz, & Chen, 1988).

Posture. The following section reviews a considerable amount of empirical literature related to postural changes potentially linked to the wearing of high-heeled shoes by participants from the general population. These studies have focused upon (a) lumbar lordosis, (b) knee flexion, and (c) head position.

Lumbar lordosis. Studies on the effects of heel height on the lumbar spine have yielded mixed results. Some studies found an increase in lumbar lordosis (an increase in the curve of the lumbar spine) as heel height increased (e.g., Pezzan, João, Ribiero, & Manfio, 2011; Lee, et al., 2001; Ebrahimian & Ghaffarinejad, 2004); however, other prominent researchers questioned the reliability of these studies due to research methods or lack of an adequate measurement tool for lumbar lordosis (Russell, 2010). Additional studies found that as heel height increased, (a) participants exhibited no significant changes in lumbar lordosis (e.g., Snow & Williams, 1994; Iunes, Monte-Raso, Sants, Castro, & Salgado, 2008), (b) some participants increased while others decreased lumbar lordosis (e.g., de Lateur, Giaconi, Questad, Ko, & Lehmann, 1991), or (c) participants decreased lumbar lordosis (e.g., Russell, Muhlenkamp, Hoiriis, & DeSimone, 2012; Bendix, Sørensen, & Klausen, 1984; Opila et al., 1988).

Opila-Correia (1990) assessed the effects of low (M = 1.6 cm, SD = 1.1 cm) and high (M = 6.1 cm, SD = 0.9 cm) heel heights on the lumbar spine with (a) women (n = 6) experienced in wearing heels three to five times per week for eight to 37 years, (b) women (n = 4) experienced in wearing heels two to five times a week for three years, and (c) women (n = 4) who were inexperienced in wearing heels. Results yielded no significant differences in lumbar lordosis between participants grouped by heel wearing experience. After the researcher assigned women into different age groups of younger (*n* = 7) and older (*n* = 7) participants, results indicated that the older group had a (a) greater degree of posterior pelvic tilt, (b) lower degree of lumbar lordosis, and (c) greater anterior upper trunk movement. The group of younger participants exhibited the opposite tendencies.

Knee flexion. Other researchers have found that wearing high heels produced increased knee flexion, or a greater bending of the knees. Stefanyshyn, Benno, Nigg, Fisher, O'Flynn, and Liu (2000) measured the kinematics, kinetics, and muscle electromyography (EMG) of female participants (*N* = 13) wearing different shoe heel heights (*N* = 4). Results indicated that while participants stood in high heels, knee flexion gradually increased and concomitantly boosted activity in the rectus femoris muscle as it attempted to control for the increased knee flexion.

Mika et al. (2012) studied the EMG activity of the lower limb muscles (rectus femoris, biceps femoris, tibialis anterior, medial gastrocnemius) in young (*n* = 31) and middle-aged (*n* = 15) adult women as they walked barefoot, and in low (4 cm) and high (10 cm) heels. The researchers found an increase in participant knee flexion as heel height increased.

Head position. No published heel study with the general population has examined exclusively the effects of heel height on head position. However, Opila et al. (1988) studied both male (*n* = 7) and female (*n* = 12) college students while barefoot and while wearing stiletto heels and noted that some participants exhibited a posterior movement of the head. The researchers found that in response to the flexed knee position initiated by heel height, participants, on average, (a) contracted the quadriceps muscles, (b) moved the head, thoracic, and lumbar spine posteriorly, (c) leaned the trunk posteriorly, (d) flattened the lumbar spine, and (e) rolled the pelvis backwards. Results indicated no significant differences in compensatory mechanisms between habitual heel wearers and less experienced heel wearers (male participants).

Iunes et al. (2008) used photogrammetry to assess if heel height experience or type of high heel affected postural angle measures. The researchers tested women who wore high heels every day (n = 20) and women who only wore high heels occasionally to social functions (n = 20). Results indicated that the head position angle (Tr – C7 – line parallel to the ground) significantly altered between all types of footwear (barefoot, platform, stiletto) and between the two experience groups. The group that wore high heels occasionally exhibited a lower head position measurement (M = 50.73 degrees) compared to the group that wore high heels every day (M = 53.15 degrees). No other angles differed significantly between groups.

Head Position and Jaw Opening: Non-Singing Contexts

Researchers in orthodontics, maxillofacial surgery, sleep apnea, and speech language pathology have explored extensively the effects of head position and jaw opening in non-singing contexts. This section will present studies on head position and jaw opening in non-singing contexts relative to (a) pain and disorders, (b) vocal tract, (c) head position and maximal jaw opening, and (d) speakers and voice disorders.

Pain and disorders. Several studies have found connections between participant head position and (a) occurrence of headaches (e.g., Watson & Trott, 1993), (b) swallowing disorders (e.g., Ekberg, 1986; Inagaki, Miyaoka, Ashida, Ueda, & Yamada, 2007), and (c) temporomandibular disorders (TMD) (e.g., Armijo-Olivo et al., 2011; Sonnesen, Bakke, & Solow, 2001).

Vocal tract. Researchers have found that alterations in head position and jaw opening elicited changes in the vocal tracts of sleep apnea and orthodontic patients. The following section outlines the empirical research in non-singing contexts on the effects of head position and jaw opening on the (a) trachea, (b) hyoid bone, (c) pharyngeal airway, and (d) tongue.

Trachea. Harris (1959) discovered that head position affected the length of the trachea. Harris studied radiographs of males ($N = 15$), ages 18 to 22 years during (a) head and neck flexion, (b) head and neck extension, and (c) inspiration and expiration. Harris found that during the head position extension and expiration condition, participants (a) elongated the infrahyoid respiratory passage by 23% (0.9 cm), which increased to 30.9% (1.1 cm) during inspiration; (b) increased the length of the trachea by 2.6 cm; (c) significantly narrowed the antero-posterior diameter of the trachea in the supraclavicular portion ($M = 16\%$) especially during expiration; and (d) exhibited no significant differences in the respiratory displacement of the larynx (elevated or lowered).

Hyoid bone. The hyoid bone, suspended by the suprahyoid and infrahyoid musculatures and typically located between the third and fourth cervical vertebrae, moves with chewing, swallowing, breathing, and phonation (Ingervall, Carlsson, & Helkimo, 1970). The hyoid bone attaches muscularly to the base of the skull, mandible, tongue, sternum, scapula, pharynx, and thyroid cartilage (Stepovich, 1965). Therefore, any movements of these attached anatomies could potentially result in hyoid bone movement (Doual, A., Léger, Doual, J. M., & Hadjiat, 2003). Opdebeeck, Bell, Eisenfeld, and

Mischelevich (1978) compared patients with short face syndrome (*n* = 9) and patients with long face syndrome (*n* = 27) and found that the hyoid, tongue, pharynx and cervical spine moved together simultaneously.

A few studies have shown that differences in head position and jaw opening corresponded with movement of the hyoid bone (Hellsing, 1989; Muto & Kanazawa, 1994). Ingervall et al. (1970) analyzed the relationship between the hyoid bone and mandible in participants (*N* = 144) grouped by dental occlusion (normal and postnormal) and age. Results indicated that the antero-posterior distance between the mandible position in recluded and intercuspal positions strongly and positively correlated with the supero-inferior movement of the hyoid bone.

Gustavsson, Hansson, Holmqvist, and Lundberg (1972) studied the radiographs of men (*n* = 8) and women (*n* = 22) as they bent the head forward and bend the head backward. Although they found no significant correlations existed between the hyoid bone movements and head position movements, results indicated that when participants bent the head forward, the hyoid bone moved forward and into a horizontal position. However, when participants bent the head backward, the hyoid bone moved backward and became more vertically oriented to the sella-nasion line.

Kollias and Krogstad (1999) examined three lateral cephalometric radiographs, taken at approximately 10-year intervals, of male (*n* = 26) and female (*n* = 24) dental students to assess craniofacial and craniocervical changes during adulthood. Results indicated that as participants aged, the hyoid bone moved inferiorly for both sexes. Vertical head position (NSL/VER) remained unchanged; however, as age increased, the head posture moved closer to the cervical spine (NSL/OPT, NSL/CVT). Cervical curvature also decreased across the three time point measurements of head position.

Tallgren and Solow (1984) studied long-term female denture wearers (*N* = 24) over the span of 15 years and found that the mandible and the hyoid bone typically moved in the same direction (e.g., an inferior movement of the mandible corresponded with an inferior movement of the hyoid bone). Although the researchers found no significant change in participant head and cervical posture over the span of 15 years, the cervical spine usually moved anteriorly and superiorly. The researchers emphasized the importance of studying the hyoid bone in relation to mandible, head, and cervical posturing.

Pharyngeal airway. The pharyngeal airway, approximately 12-14 cm in length, has three sections: (a) nasopharynx, (b) oropharynx, and (c) laryngopharynx. It begins at the cranial base, and ends at the lower border of the cricoid cartilage around the sixth cervical vertebra. Pharyngeal airway occlusion can limit the ability to breathe, a consideration applicable to sleep apnea patients who may compensate for an occlusion in the pharyngeal airway by (a) extending the head, (b) moving the tongue forward and downward, and (c) moving the mandible forward and downward (Ceylan & Oktay, 1995). Therefore, a majority of research in pharyngeal airway space has been conducted by sleep apnea researchers.

Tong, Sakakibara, Hix, and Suetsugu (2000) studied sleep apnea patients (*n* = 86) and healthy patients (*n* = 37) and found that sleep apnea patients exhibited a significantly narrowed upper airway and forward inclination of the cervical column. Results indicated significant positive and negative correlations (depending upon the angle of measurement) between head posture and airway dimensions. The researchers concluded that sleep apnea patients might use extended head position postures to maintain airway patency.

Behlfelt, Linder-Aronson, and Neander (1990) assessed children with enlarged tonsils (n = 22) against a control group (n = 22). Results indicated that children with enlarged tonsils (a) tended to mouth breathe at night (n = 82%), (b) displayed extended head posture, (c) had a lowered position of the hyoid bone, and (d) exhibited an antero-inferior tongue posture. The researchers concluded that the children adapted to the extended head posture and resulting configuration of the vocal tract in order to maintain a free oro-pharyngeal airway.

Hellsing, Forsberg, Linder-Aronson, and Sheikholeslam (1986) examined head position, mandibular position, and the muscle activity of adults (N = 30) while breathing normally, after obstruction of the nasal airways, and after removal of the obstruction of the nasal airways. Results suggested that during the obstruction of the nasal airways, participants (a) extended head position, (b) lowered the mandible, and (c) exhibited greater EMG activity in the suprahyoid muscles. The researchers concluded that breathing mode could affect head and mandible postures.

Hellsing (1989) studied lateral skull radiographs of male and female adults (N = 20) during their natural head positions and with a head position extended by 20 degrees to explore any potential relationships between (a) cervical lordosis, (b) craniocervical inclination, (c) hyoid bone, and (d) pharyngeal airway space. They found that during the extended head position condition, participants, on average, (a) increased cervical lordosis, (b) increased the distance between the hyoid bone and the fourth cervical vertebra, (c) increased the cross-sectional airway dimensions, and (d) exhibited a small increase in the space between the posterior pharyngeal wall and the dorsal surface of the tongue.

Muto et al. (2002) studied lateral cephalometric radiographs of adults (*N* = 10) during five different head postures. Results indicated that head extension (OPT/NSL and C3-Me) measurements correlated significantly, strongly, and positively with the dimensions of pharyngeal airway space (PAS-TP). They concluded that a 10 degree increase in cranio-cervical inclination (OPT/NSL) resulted in an approximate increase of 4 mm in pharyngeal airway space.

Muto et al. (2006) used lateral cephalometry to examine the relationship between craniofacial and pharyngeal airway space measurements with dental students (*N* = 60). The researchers found that pharyngeal airway space measurements significantly correlated with the (a) hyoid position, (b) maxillary and mandibular size and prognathism, and (c) mandibular inclination. An increase in the mandibular inclination (i.e., a forward jaw position) resulted in an increased pharyngeal airway space.

Tongue. Shelton and Bosma (1962) examined lateral radiographs of male (*n* = 5) and female (*n* = 5) college students in five conditions: (a) upright and still position, (b) elevated head position, (c) lowered head position, (d) displacement of mandible and tongue, and (e) fixation with increased intrathoracic pressure. Results indicated that the elevated head position elicited a distinctive pharyngeal airway expansion, and that the dorsal portion of the tongue was the principle component in the regulation of the dimensions of the pharyngeal airway. Some participants exhibited pharyngeal airway expansion from the level of the palate to the laryngeal vestibule.

Head position and maximal jaw opening. Several studies have found a relationship between head position and maximal jaw opening. Muto and Kanazawa (1994) assessed changes in the positioning of the hyoid bone during closed and maximal mouth-opening positions with dental students (*N* = 60). Results indicated that at maximal mouth opening, the hyoid bone moved posteriorly and inferiorly in comparison to the closed mouth position. During the maximal jaw opening condition, Muto and Kanazawa also found that all participants exhibited a posterior change in head position. They concluded that maximal mouth opening was impossible without a concomitant change in head position.

Goldstein, Kraus, Williams, and Glasheen-Wray (1984) observed the head posture and mandibular closure of participants (*N* = 12) with both normal and forward head postures. Goldstein and colleagues concluded that a change in the anteroposterior head position altered at least one component of mandibular closure.

Eriksson, Zafar, and Nordh (1998) tested participants (*N* = 12) during maximal jaw opening and closing tasks at slow and fast speeds. The researchers found that jaw opening occurred with head extension while jaw closing occurred with head flexion.

Eriksson, Häggman-Henrikson, Nordh, and Zafar (2000) studied healthy adults (*N* = 12) during three modes of jaw opening and closing tasks including chewing. Participants, on average, moved their head positions posteriorly immediately before jaw opening and continued in this pattern until they completed the jaw opening and closing tasks.

Zafar, Nordh, and Eriksson (2000) examined the head position and jaw opening coordination in healthy individuals (*N* = 25). The researchers found that participant head position moved concurrently with or immediately before the mandible during jaw opening and closing tasks.

Kohno, Matsuyama, Medina, and Arai (2001) examined male adults (*N* = 4) during jaw opening and closing tasks by tracking upper and lower incisal markers. Results indicated that the head moved rhythmically with the mandible. Head extension accompanied jaw opening, and head flexion correlated strongly with jaw closing.

Speakers and voice disorders. A few researchers have studied the relationship between speaking voice and posture. Lagier et al. (2010) studied healthy participants (*N* = 20) executing speaking tasks in three listener distance and background noise conditions: (a) listener at 4 m, background noise of 44 to 48 dB SPL; (b) listener at 10 m, background noise of 44 to 48 dB SPL; and (c) listener at 10 m, background noise of 90 dB. As participants increased vocal effort measures of fundamental frequency, closed quotient, and SPL in order to be understood, they altered their postures by bending the trunk forward and rotating the head backward, which consequently increased the cervicocephalic angle.

Miyaoka S., Hirano, Miyaoka Y., and Yamada (2004) tested women (*n* = 7) and men (*n* = 7) as each participant (a) opened the jaw to its maximum extent, and (b) completed three phonation tasks using /pa/, /ta/, and /ka/. The researchers found two phases of head tilt associated with the two tasks: (a) initial posterior head tilt and (b) sustained posterior or anterior rhythmic head tilts.

Other studies have examined differences in body posture exhibited by participants with healthy speaking voices and those with voice disorders. Kooijman et al. (2005) studied female teachers (*N* = 25) with persistent voice complaints and found that anteroposition of the head (found in 70% of the participants) proved to be one of the most common predictors for a low Dysphonia Severity Index score. Paseman, Casper, Colton, and Kelley (2004) measured the effects of horizontal head movement on the glottal closure of unilateral vocal fold paralysis patients ($N = 10$). Results indicated that head position did not improve glottal closure.

Lin, Jiang, Noon, and Hanson (2000) examined the effects of head extension and tongue protrusion, a posture common for patients undergoing rigid videolaryngoscopy, on voice perturbation measures. The researchers recorded sustained vowels from vocally healthy women ($n = 46$) and men ($n = 66$). Results indicated that head extension (a) increased fundamental frequency, and (b) decreased shimmer. The researcher concluded that head-tongue position should be considered in voice measurements.

Head Position and Jaw Opening: Singing Contexts

The matters of ideal head position and jaw opening for singers have elicited much speculation and anecdotal advice. However, fewer experimental studies have been conducted in this area with singers than with participants from the general population. The following section reviews extant research literature on singer head position and jaw opening with regard to (a) vocal style and registration, (b) perception of vocal timbre, (c) pitch and vowel, (d) spectral energy, and (e) formant tuning.

Vocal style and registration. Some studies have shown that participants altered head position and jaw opening when asked to perform different vocal styles and registrations. Echternach, Popeil, Traser, Wienhausen, and Richter (2014) used MRI to study a single soprano participant in four experiments where she (a) performed the vowel /e/ from G3 to C6 in both head voice and belt, (b) sang the vowels /a, e, i, o, u/ in a descending triad on the pitches C5, G4, E4, and C4 in modal and head registers, (c) sustained the vowel /a/ on the pitch C4 with a neutral, constricted, and widened pharyngeal position, and (d) sustained the vowel /ae/ on the pitch G4 using two vibrato styles (jazzy and classical). Results from the first experiment indicated that the vocal tract shape altered between the two styles (head voice and belt). During the belt condition, the singer exhibited greater lip opening and greater jaw opening. The singer also increased lip and jaw opening as pitch ascended, regardless of style. The pharyngeal width narrowed and the larynx elevated for belt singing. Results from the second experiment indicated that for most vowels sung in the modal register compared to the head register, the participant increased lip opening and pharyngeal width. The participant reported she felt uncomfortable while singing in the supine position, in a noisy environment, and with a constraining neck brace.

Echternach, Traser, and Richter (2014) studied professional operatic tenors (*N* = 4) using MRI as they sang ascending major scales on the vowels /a, e, i, o, u ae/ from C4 (262 Hz) to A4 (440 Hz) with purposeful changes in register shifts. Results indicated increased measurements of jaw and lip opening for vowels with high F1 frequencies (/a/ and /ae/) compared to vowels with low F1 frequencies (/i/ and /u/). The researchers also found that when they asked participants to stay in modal voice ("stage voice") across the passaggio (E4-F4), participants exhibited a greater amount of lip and jaw opening compared to when they shifted to the falsetto register. Measurements of tongue dorsum height, jaw protrusion, uvula, and larynx angle displayed small deviations between register conditions. Pharyngeal width increased as pitch ascended when participants sang in stage voice above the passaggio on the vowel /a/; however, on vowels /e/ and /i/, two participants increased and two participants decreased pharyngeal width as pitch ascended.

Perception of vocal timbre. Other studies have shown that head position and jaw opening affected the perception of vocal timbre. Barnes-Burroughs, Watts, Brown, and LoVetri (2005) studied listener perceptions ($N = 2$) of singers ($N = 8$) performing songs with purposeful head movements: (a) head position following the normal melodic curve of the score, (b) head and neck in an elevated posture for the duration of the song, (c) head and neck in a downcast posture for the duration of the song, and (d) head position following the inverted melodic curve of the score. The classical voice pedagogue listener favored the downcast head position or inverted melodic contour posture. The musical theatre pedagogue expressed idiosyncratic preferences and favored the elevated head posture in some participants. No listener preferred the head position following the natural melodic contour.

Rollings (2012) recorded a soprano ($N = 1$) twice singing a song with three different head positions: (a) lowered, (b) neutral, and (c) elevated. The mean LTAS data indicated that the lowered head position dampened the overall mean signal amplitude, while the elevated head position increased mean signal amplitude with individual harmonic differences up to 5.75 dB. Rollings then surveyed vocal timbre preferences of university music majors ($N = 30$) as they listened to pairs of the soprano recordings in each of the three head position conditions. After the researcher added listener preference selections for vocal timbre across all recordings, results indicated that the neutral head position performances received the highest number of selections (neutral [$n = 121$ selections], lowered [$n = 95$ selections], elevated [$n = 87$ selections]).

Pitch and vowel. Five studies to date have found that singers altered head position and jaw opening with changes in pitch and vowel. Curry (1937) analyzed radiographs of a soprano (*N* = 1) singing the vowel [ɑ] on eight pitches ranging from 208 to 1024 Hz. Results indicated that (a) jaw and lip opening increased as pitch ascended, (b) the pharynx and laryngeal vestibule openings consistently narrowed on the lowest and highest pitches, and (c) the hyoid bone, larynx and longitudinal cartilages moved upward as pitch ascended.

Austin (2007) explored whether the experience level of singers could affect the amount of superior-inferior jaw opening employed. He tested novice (*n* = 6) and experienced (*n* = 6) participants while speaking and while singing low, medium, and high pitches on three vowels ([a], [i], [u]). Results suggested that novice and experienced singers did not differ significantly in jaw opening measurements; however, participants significantly increased jaw opening based on (a) vowel (with a greater degree of jaw opening for [a] compared to [i] or [u]), and (b) pitch (with a greater degree of jaw opening for medium and high pitches compared to low pitches).

Honda, Hirai, Masaki, and Shamada (1999) used MRI to study male participants (*N* = 3) as they performed low and high frequencies on the vowel /a/. Results indicated that while singing the low frequency, participants (a) lowered the jaw, (b) moved the larynx vertically, and (c) rotated the cricoid cartilage along the cervical lordosis. While singing the high frequency, participants (a) moved the hyoid bone horizontally and (b) kept the larynx height comparatively constant. The researchers concluded that spinal curvature contributed to vocal function relative to pitch.

Scotto Di Carlo (1998) used X-ray to measure the cervical spines of professional singers (n = 12), beginning singers (n = 12), and non-singers (n = 12) at rest and during phonation of the French cardinal vowels in speaking voice and singing voice (lower, medium, and upper pitch ranges). Results indicated that as participants ascended in pitch, all professional singers (a) exhibited a larger buccal opening, (b) elevated the head, (c) posteriorly shifted the cervical spine, (d) posteriorly and superiorly shifted the occiput, and (e) displayed a cervical curvature inversion. Beginning singers followed the same trends as professional singers but to a much lesser degree. They did not display any cervical curvature inversion. All professional singers and some beginning singers exhibited cervical spine abnormalities. None of the non-singer participants exhibited cervical spine abnormalities. Scotto Di Carlo reasoned that all participants increased the craniocervical angle as pitch ascended due to increased jaw opening. She suggested that cervical inversion occurred on the upper pitches due to a singer's need to create space for pharyngeal widening and the forward tilt of the thyroid cartilage. She concluded that professional singers exhibited cervical spine abnormalities due to cervical deformations during extended periods of rigorous singing that eventually became part of the singer's corporal schema and that any cervical surgery may prevent the movement of the cervical spine, which could have a direct impact on the singing voice, especially in the higher frequencies.

Scotto Di Carlo (2002) examined a coloratura soprano, the one participant of the former study who reacted in the opposite way from all of the professional singers by lowering her head position to sing higher pitches. The X-ray images of this participant showed a high degree of calcification of the larynx, especially in the area of the cricothyroid joint, thus limiting laryngeal mobility. Scotto Di Carlo concluded that this soprano used a forward tilting head position to assist with the forward tilting of the thyroid cartilage necessary for ascending in pitch.

Johnson and Skinner (2009) took Roentgen-cephalograms of opera singing students, including women (n = 12) and men (n = 6), during vocal production. Results indicated that cranio-cervical angles while singing differed significantly from baseline (quiet) measurements. When singing, participants, on average, tended to (a) increase cranio-cervical angulation (M = 6.93 degrees), (b) move the head forward (M = 7.20 degrees), (c) increase pharyngeal airway space, and (d) alter the position of the hyoid bone. The researchers concluded that opera singers should be aware of the potential risks of cervical spine surgery as it may impact voice quality.

Miller et al. (2012a) used magnetic resonance imaging (MRI) with supine singer and non-singer, male and female participants (N = 10) to study the effects of humming low and high pitches on the vocal tract and its related structures including head and neck position measurements. The researchers removed the potential confounding variable of articulatory or postural changes by using humming. Results indicated that when participants hummed high notes compared to low notes, they significantly (a) increased craniocervical angles (opt/nsl and cvt/nsl), (b) widened the distance between the C3 vertebra and the menton (inferior point of the bony chin) and between the sternum and the hyoid bone, and (c) exhibited a laryngeal and hyoid bone elevation relative to the cranial base. The researchers found significant, moderate, positive correlations between vocal tract and craniocervical structures. Miller and colleagues concluded that during voice production, synchronized, pitch-dependent structural adjustments occurred unrelated to articulatory or postural modifications. The researchers noted that the one professional singer participant responded in an opposite way from the other participants on the variables found to be significantly different between low and high note humming conditions. The researchers posited that this behavior could be due to understanding that trained singers use a technique that encourages a low larynx. Miller and colleagues reiterated that research studies should account for pitch and articulation in voice production separately.

Miller et al. (2012b) published a secondary study using the same data previously mentioned, but aimed to test the validity of using MRI (soft tissue definition) in conjunction with cephalometic data (bony reference points) to measure vocal tract, craniofacial, and cervical spine structures. Results indicated positive, moderate correlations between vocal structures, the craniofacial skeleton, and the cervical spine. The researchers considered this new MRI method validated and reiterated the importance of considering the wider context of craniofacial skeleton, cervical spine, and sternum structures when researching functional activity during voice production.

Spectral energy. Another group of studies indicated that an adjustment in head position could alter the spectral energy of a complex vocal sound. Jones (1972) conducted an Alexander method head repositioning experiment where he manually pulled up the base of the head of one singing female participant. Jones found (a) improved integrity of spectral harmonics, (b) increased richness of overtones, and (c) disappearance of breath noise.

Luck and Toiviainen (2007) conducted a motion capture pilot study that studied the relationship between kinematic postural elements (*n* = 14) and measures of vocal timbre (*n* = 4) with singers (*N* = 15) as they performed a short song. Results indicated that the lateral head angle was a significant predictor of voice timbre (spectral irregularity and rms amplitude) in individual participants, more than any other kinematic variable. When participants sang with a lowered head position, they exhibited increased spectral irregularity; however, when participants sang with an elevated head position, they showed an increase in rms amplitude. The researchers hypothesized that the increase in amplitude found with an elevated head position could have been related to a freeing up of the vocal apparatus that permitted greater airflow.

Rollings (2014b) studied university voice majors (*N* = 30) as they performed the same song in three head position conditions (lowered, neutral, and elevated). Results indicated that compared to the lowered head position, the elevated head position produced (a) superior head movement, (b) posterior neck movement, (c) decreased jaw opening, (d) increased mean LTAS signal data, and (e) increased frequencies for F1- F3, and decreased frequency for F4 on the pitch of C4 and the vowel [ɑ].

Formant tuning. Vocal scores provide singers with pitches and rhythms for the standard song and operatic repertoire. Additionally, singers must maintain some sense of linguistic accuracy in order to be understood and communicate the text of a vocal work. Vocal literature commonly requires female singers to produce pitch and vowel combinations where the fundamental frequency (F_0) lies higher than the first formant frequency of many vowels. For example, the first formant of the [ɑ] vowel resides around 730 Hz (see Table 1), the highest first formant frequency of any standard English vowel. When a female sings a "high C" (C6) on the vowel [ɑ], the fundamental frequency (1046 Hz) lies much higher than the first formant frequency (730 Hz). Therefore, the first formant frequency for female singers typically exceeds the fundamental frequency on pitches above F#5 (739.99 Hz) for the vowel [ɑ]. The [i] vowel has a much lower first formant frequency at approximately 270 Hz (see Table 1). Therefore, on the [i] vowel, the first formant frequency typically exceeds the fundamental frequency on pitches above C#4.

Table 1.

Formant Frequencies of American English Vowels

IPA Symbol	**Example Word**	**F1 (Hz)**	**F2 (Hz)**	**F3 (Hz)**
ɔ	hawed	570	840	2410
u	hoot	300	870	2240
ʊ	hood	440	1020	2240
ɑ	hot	730	1090	2440
ʌ	hut	640	1190	2390
ɝ	heard	490	1350	1690
æ	hat	660	1720	2410
ɛ	head	530	1840	2480
ɪ	hit	390	1990	2550
i	heed	270	2290	3010

Note. Peterson and Barney (1952) measured formant frequencies of speakers (*N* = 70) as they pronounced ten words.

In contrast to female singers, a tenor "high C" (C5) on the vowel [ɑ] allows the fundamental frequency (523 Hz) to stay below the first formant frequency (730 Hz). Trained male singers typically couple F3, F4, and F5 (commonly called the "singers' formant") to increase energy in the area from 2 to 4 kHz where the human ear is most sensitive. This "singers' formant" resonance strategy boosts sound intensity without extra effort (Sundberg, 1975).

The resonance strategy of using the "singers' formant" would not be effective at high pitches for female voices because of the widely spaced harmonics. Instead, female singers employ a resonance strategy called formant tuning. Formant tuning occurs when the singer reaches the frequency where F_0 would exceed F1 (Weiss, Brown, & Morris, 2001). At this point, the singer increases or tunes the frequency of the first formant to be slightly higher than the fundamental frequency, which subsequently boosts dB SPL (up to 30 dB) without requiring more vocal effort (Sundberg, 1987). Formant tuning maintains the vocal fold inertive load and enhances their vibration (Titze, 1998).

Studies have shown that listeners found it difficult to identify vowels at high frequencies due to the vowel modification singers employed in order to formant tune (Scotto di Carlo & Germain, 1985; Benolken & Swanson, 1990). Richard Wagner consciously or subconsciously aided formant tuning when composing his soprano roles by setting the text for high pitches with high first formant frequency vowels (Smith & Wolfe, 2009).

Researchers have suggested that jaw opening raises the first formant frequency, which may aid in formant tuning. Lindblom and Sundberg (1971) analyzed X-ray data from the sustained vowel articulations of a Swedish speaker ($N = 1$) in order to create a model of the relationships between the articulators and formant frequency measurements. The researchers concluded that with all other factors constant (lip position, larynx height, etc.) an increase in jaw opening corresponded with an increase in F1, in some cases by several hundred Hz. The tongue created the most change in F2, dependent on its positioning in the mouth. An increase in the amount of constriction in the mouth (relative to the palate) also corresponded with an increase in F2. When the larynx lowered by 10 mm, all formant frequencies decreased.

Sundberg (1975) used multiple methods to measure the formant frequencies (F1–F3) of a professional soprano (*N* = 1) as she "sang silently" six vowels [u, o, a, ɑ, e, I, y] on four frequencies (262, 394, 523, and 698 Hz) in an anechoic chamber. Results suggested that the soprano tuned the first formant frequency to the approximate location of the fundamental frequency. Sundberg concluded jaw opening to be an essential articulatory method for alteration of the first formant frequency. All vowels produced a jaw opening that increased as pitch ascended, except the vowel [ɑ] where jaw opening stayed consistent across frequencies. Jaw opening also increased with a rise in intensity. Lip opening increased with pitch, and [ɑ] exhibited the most lip opening while [u] exhibited the least lip opening.

Sundberg and Skoog (1997) examined the jaw openings of professional singers of various voice classifications (*N* = 10) as they sang ascending two octave scales on the vowels /ɑ/, /a/, /o/, /u/, /i/, /e/. Because the researchers could not measure formant frequencies at higher pitches, they measured F1 for the lowest pitch that each participant sang and questioned if participants would increase jaw opening as the F_0 approached, equaled, and was greater than the calculated frequency of F1. Results indicated that participants did increase jaw opening while singing vowels /ɑ/ and /a/ as F_0 approached F1. Similarly, most participants increased jaw opening approximately five semitones above the F1 measurement of the lowest sung F_0 for vowels /e/ and /o/. For the vowels /i/ and /u/, which have the lowest first formant frequency, participants only increased the jaw opening in the upper pitch range. The measurements of jaw opening varied across singers with one participant using 25 mm of jaw opening to produce the vowel /u/ while others only used 5 mm. Sundberg and Skoog concluded that one of the reasons singers increased jaw opening on /ɑ/ and /a, but not on /u/ and /i/ could be a reduction in tongue constriction that more readily raised F1 in these vowels without requiring a jaw movement. They commented that if the singers reduced tongue constriction with the open vowels of /ɑ/ and /a/, it would have had the opposite effect and lowered F1, which would be contrary to what a soprano would need acoustically at higher fundamental frequencies.

In contrast to Sundberg and Skoog (1997), Bresch and Narayanan (2010) used real-time (RT) MRI to investigate supine soprano participants (*N* = 5) singing two octave scales on the syllables /la/, /le/, /li/, /lo/, and /lu/ without vibrato. Results indicated that for low pitches, each vowel had a clear vocal tract configuration. However, as pitch ascended these distinctions between vowels became less clear and the oral cavity became wider. The researchers found that as pitch ascended for vowels /i/ and /u/, (a) the first formant increased and (b) the opening of the oral cavity widened. However, the researchers concluded that they could not find any other generalizable strategies for resonance tuning across participants because oral cavity width varied depending on the singer.

Sundberg (2009) assessed the effects of pitch on articulatory configuration using MRI with a professional soprano (*N* = 1) in the supine position as she sang the vowels /i/, /e/, /u/, /o/, /a/ on an ascending triad pattern from C4 (262 Hz) to G5 (784 Hz). Results indicated that as pitch ascended, the singer (a) reduced tongue dorsum height on vowels /i/, /e/, /u/, and /a/, (b) widened lip opening on the vowels /o/ and /a/, and (c) widened jaw opening on the vowel /a/. For higher pitches, the singer widened the jaw opening for all vowels. The singer began to widen the jaw opening approximately four or five semitones below the F_0 that equaled her normal F1 value for each vowel (determined from the lowest sung pitch).

Heel Height: Singers

Two studies to date have examined the effect of high heels on head position and acoustical measures of female singers. Rollings (2014a) conducted a collective case pilot study using female voice majors ($N = 5$) singing their own audition arias and wearing their own shoes of three different heel heights (low [< 0.5 in.], medium [1.0 - 1.5 in.] and high [> 1.5 in.]). Results indicated that all participants exhibited postural changes in lumbar lordosis and knee flexion. Head position measurements revealed the largest differences as four out of five participants decreased head position measurements in high heel conditions compared to barefoot conditions. A majority of participants ($n = 4$, 80%) displayed significant differences in LTAS data between low and high heel conditions. Formant frequency data yielded idiosyncratic shifts for F1-F4. Perceptually, no singer mentioned that heel height could affect vocal production, but some singers ($n = 3$) said that it could impact how they might feel in a performance. A majority of singers ($n = 4$, 80%) preferred the medium heel height (1.0 – 1.5 in.) for singing.

Rollings (2013) tested the effects of barefoot and heel conditions (4 in.) on female singers ($N = 30$) in silent and singing conditions as they performed the same song. All participants (100%) decreased head position when singing in high heel as opposed to barefoot conditions. From silent to singing conditions, participants significantly increased head position measurements. Participants exhibited an even greater degree of head position movement from silent to singing conditions in high heel as compared to barefoot conditions. The researcher speculated that participants may have exhibited a greater increase in head position from silent to singing conditions while wearing high heels due to the lowered head position elicited by increased heel height. Therefore, high heels could have required participants to exhibit a greater head position adjustment in order to open the jaw to sing. Acoustically, (a) most participants lowered F1- F3, and (b) LTAS data of each averaged harmonic across participants differed significantly between conditions. Most participants felt they sang best while barefoot (n = 21, 70.00%).

Summary

A review of pertinent research literature has indicated that heel height, head position, and jaw opening have interested investigators in a variety of disciplines. However, comparatively fewer studies have focused on these matters with particular reference to singers.

Although some studies in non-singing contexts have found moderate to strong relationships between head position, jaw opening, and dimensions of the vocal tract, and although some studies with singers have indicated that jaw opening (a) changes with pitch and vowel, (b) may alter the first formant frequency, and (c) may assist in formant tuning for female voices, no empirical study to date has examined heel height, head position, and jaw opening simultaneously with female singers using both postural and acoustical measures. Such a study could be of considerable interest to singers, singing teachers, and researchers.

CHAPTER THREE

Method

The purpose of this study was (a) to determine the effects, if any, of three simulated heel height conditions (0.0 in., 1.5 in., 3.0 in.) on postural (head position, jaw opening) and acoustical (LTAS, dB SPL) measures of university female voice majors (*N* = 35) in two conditions (silence, singing sustained [ɑ] and [i] vowels on each pitch of a 2-octave A-major scale [A3-A5]), and then to (b) assess selected relationships between heel height behavior conditions, postural data, and acoustical data. This chapter describes the research design, independent and dependent variables, procedures, equipment, and data analyses pertinent to this study.

Participants

Participants (*N* = 35) constituted a convenience sample of female voice majors from a large Northeastern collegiate music program. Participants ranged in age from 18 (*n* = 2) to 31 (*n* = 1) years of age (*M* = 22.03 years, *SD* = 2.91 years). All participants identified themselves as music majors with voice as a primary instrument. Participants included undergraduate (voice performance [*n* = 9], music education [*n* = 6], music with voice emphasis [*n* = 5]) and master's (voice pedagogy and performance [*n* = 13], voice performance [*n* = 1], voice pedagogy [*n* = 1] students. Participant's self-reported years of one on one vocal training ranged from 2.5 years (*n* = 1) to 15 years (*n* = 1) (*M* = 6.94 years, *SD* = 3.00 years).

An Institutional Review Board (IRB) approved this study prior to beginning data collection (see Appendix B). Participants signed a consent form (see Appendix C) that stated the purpose of this study as assessment of "acoustical changes in singers." This initial description of the study did not inform participants beforehand of the independent (heel height) variable of interest.

Procedures and Equipment

Heel height simulation. Manufactured shoes present numerous confounding variables for researching potential differences between two or more shoe heel heights. For example, although the same style shoe may be offered in heel heights of 1.5 in. and 3.0 in., the higher-heeled shoe may have extra built-in support, a slightly higher heel, or a slightly wider heel base. By using wooden boards that simulated heel height instead of manufactured shoes, this study eliminated confounding variables of shoe construction, heel width, heel type, shoe fit, or style and focused solely on any potential differences produced by changes in vertical heel height.

Therefore, following Bendix et al. (1984), this study simulated heel height as participants stood in ballet slippers on pieces of wood that simulated 0.0 in., 1.5 in., and 3.0 in. heel heights. Participants wore black leather, full-soled, “Spotlights” ballet shoes manufactured by American Ballet Theatre that featured a canvas lining and elastic band for a secure fit. I offered this brand of ballet shoes in all sizes, including half sizes, from US 7-10. I also offered children sizes 4 and 4.5, which corresponded to adult sizes 6 and 6.5. The ballet shoes had never been worn prior to the study. The ballet shoes offered a more naturalistic feeling and protected the foot while the participant stood on the wooden boards.

The wooden boards remained in a parallel position on a taped line with 6.0 in. distance between them. I used masking tape to mark the positioning of the wooden boards to ensure the same width and placement for all wooden boards, across all trials, and across all singers.

Figures 7 through 9 illustrate the wooden heel height simulators, which consisted of two pieces (foundational board, heel height attachment) screwed together. All heel height simulator boards measured 12 x 6 x .75 in. The 0.0 in. condition did not include a heel height attachment, but required that the participants stand on the flat foundational board to simulate similar conditions across heel heights. For the 1.5 in. condition, the heel height attachment measured 1.5 x 3.33 x 1.33 in., while the heel height attachment for the 3.0 in. condition measured 3 x 3.33 x 1.33 in.

Figure 7. 0.0 in. simulated heel condition.

Figure 8. 1.5 in. simulated heel condition.

Figure 9. 3.0 in. simulated heel condition.

Singing task. Participants performed two-octave ascending A-major scales (A3-A5) on two vowels ([ɑ], [i]). I randomly chose approximately half of the participants (*n* = 18) to begin the first scale in each condition on [ɑ] followed by a second scale on [i]; with the other participants (*n* = 17) directed to begin the first scale in each condition on [i] followed by [ɑ]. I gave participants a tempo of 60 bpm before each scale using a digital metronome. I instructed all participants to sustain each note of the scale for three beats (3 s), breathe on beat four, and continue to the next pitch on the following downbeat (see Figure 10).

Figure 10. Singing task of a two-octave A-major scale (A3-A5) on vowels [ɑ] and [i].

Audio recording. I recorded all performances with a Countryman E6 omni-directional head-mounted microphone positioned out of the direct air stream, 5 cm from the left side of the participants' lip corner. The microphone connected to a Tascam US-122MKII Audio/MIDI interface pre-amplifier. I calibrated the microphone prior to each data collection using a Larson-Davis CAL200 microphone calibrator and the recording level remained consistent across all participants. I recorded all singing tasks in .wav format with a 44.1 kHz (32 bit) sampling rate with Audacity software (version 1.3.14-beta) on a MacBook Pro computer.

Video recording. I recorded participant head position and jaw opening in .mov format using a digital Zoom Handy Video Q3 camera. The video camera remained in a consistent position during each participant's data collection. I transferred all video recordings to a MacBook Pro computer and used QuickTime (version 10.1) to achieve still picture screenshots for postural analyses.

Head position and jaw opening markers. Because X-Ray measurements entail radiation and because MRI technology requires participants to be in a supine position, neither appeared appropriate for this study. Therefore, I followed Cuccia and Carola (2009), who validated a method of measuring participant head position with the use of postural markers, video recording or photography, and angle measurements.

I adhered three postural markers to measure head position: (a) a PomPom (white, 25.4 mm, with an Avery ole Reinforcement label [florescent pink, ¼ in., with a symmetrical open circle in the middle facilitating exact measurement] adhered to the approximate location of the C7 vertebra; (b) an Avery Hole Reinforcement label (white, ¼ in., with a symmetrical open circle in the middle facilitating exact measurement) adhered to the right tragus; and (c) one PomPom (white, 4 mm, with a black point drawn on the right lateral side) adhered to the nasion (bridge of the nose) (see Figure 11). In order to measure jaw opening, I adhered a fourth PomPom postural marker (white, 4 mm, with a black point drawn on the right lateral side) to the mental protuberance (chin) of the mandible (see Figure 12).

Performance protocol. Singers entered a quiet research room (ambient noise < 30 dB), having previously warmed up. All singers stated that they felt vocally and physically healthy at the time of the study. After obtaining a signed consent form and having the participants fill out a brief demographic survey (see Appendix D), I gave participants two minutes to sing in the research room to become accustomed to the room environment and acoustics.

Singers practiced the vocalization task once before beginning the study to confirm that they felt comfortable singing the scale on each vowel. After participants selected the ballet shoes they found most comfortable, I attached the postural markers and secured the head microphone.

Before beginning the singing task in each heel height, participants stood quietly for five seconds in order to obtain video of head position and jaw opening during silent conditions. Participants performed the singing task a total of six times (two times in each heel height condition). I randomized the heel height conditions using an incomplete repeated measures Latin Square design to control for order effect (see Table 2).

Table 2.

Incomplete Repeated Measures Latin Square for Randomized Order of Heel Height Conditions

Groups	1	2	3	4	5	6
A	0.0	1.5	3.0	0.0	1.5	3.0
B	1.5	3.0	0.0	1.5	3.0	0.0
C	0.0	3.0	1.5	0.0	3.0	1.5
D	3.0	1.5	0.0	3.0	1.5	0.0
E	1.5	0.0	3.0	1.5	0.0	3.0
F	3.0	0.0	1.5	3.0	0.0	1.5

Data Analyses

Postural analyses. Following Cuccia and Carola (2009), I created still picture screenshots from video recordings of participant head position and jaw opening at the midpoint of the steady state portion of each vowel (n = 2) sung on each pitch (n = 15 per scale) in each heel height condition (n = 3). I also created a still picture screenshot for the silent condition in each heel height where the participant stood quietly before beginning to sing. I viewed and measured each screenshot with Onde Rulers, an on-screen ruler program with a protractor (version 1.12.21). For each heel height condition, I obtained mean data from the two repetitions of the singing task to control for possible one-time variations.

Head position analysis. The head position angle 1 measurement (HP 1) indicated vertical (up and down) head position differences by measuring the degrees between the vertical plane (VP), tragus (Tr), and nasion (Na). An increase in angle 1 measurements corresponded with a superior movement of the chin, while a decrease indicated an inferior movement of the chin. The head position angle 2 measurement (HP 2) indicated horizontal (forward and back) head and neck position differences between the approximate location of the C7 vertebra (C7), Tr, and VP. An increase in angle 2 head position measurements corresponded with an anterior movement of the head and neck, while a decrease indicated a posterior movement of the head and neck (see Figure 11).

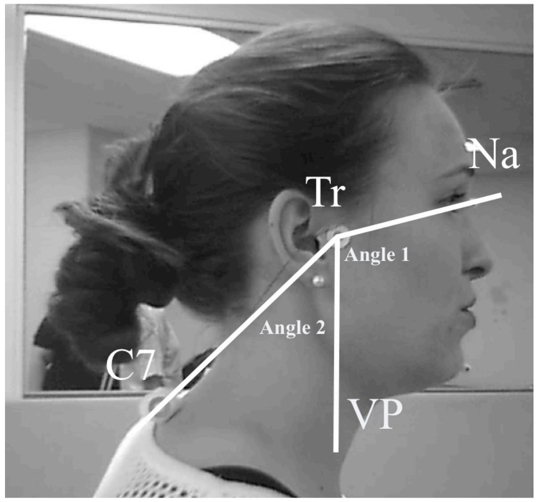

Figure 11. Head position postural markers and measurement angles.

Jaw opening analysis. Figure 12 shows the process by which I calculated jaw opening (JO), measuring the displayed degrees between the nasion (Na), tragus (Tr), and the mental protuberance of the mandible (Chin). An increase in the jaw opening angle measurement corresponded with a more open buccal cavity and a lowering of the mandible and a decrease the jaw opening angle measurement corresponded more closed buccal cavity and an elevation of the mandible.

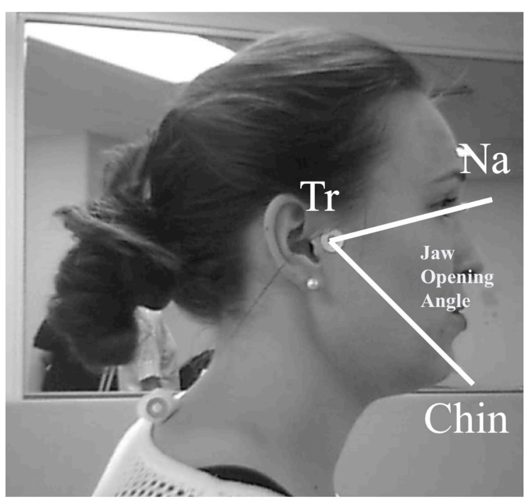

Figure 12. Jaw opening postural markers and measurement angle.

Acoustical analysis 1: LTAS. During phonation, the vocal folds produce complex sound spectra, which include resonance frequencies in addition to fundamental frequencies. Formants, or areas of acoustical energy determined by the dimensions of the vocal tract, boost some harmonic frequencies and dampen others. Generally speaking, a formant will boost the harmonic(s) closest to its frequency (Hz). For example, the first formant of the vocal tract shape for the vowel [ɑ] typically resides around 730 Hz for female singers. One would expect harmonics near the frequency of 730 Hz to be amplified by the first formant. The same principle applies to F2 – F4. Therefore, it makes sense that if differences in head position, jaw opening, vowel, pitch, or heel height could alter the dimensions of the vocal tract, a concurrent change in formant frequency could occur thereby shifting the amplitude of harmonics.

Long-term average spectra data represent a sampled average of spectral harmonic amplitude over time that minimizes short-term variations due to the phonetic structure, thus displaying persisting spectral events (Löfqvist & Mandersson, 1987). Studies have shown that LTAS data vary among (a) various singing styles (e.g., Cleveland, Sundberg, & Stone, 2001), (b) voice classifications (e.g., Johnson & Kempster, 2010), (c) singing experience level (e.g., Barnes, Davis, Oates, & Chapman., 2004; Mitchell & Kenny, 2008; Thorpe, Cala, Chapman, & Davis, 2001; Brown, Rothman, & Sapienza, 2000; Mendes et al., 2003; Oliveira Barrichelo, Heuer, Dean, & Sataloff, 2001), (d) age groups (e.g., Linville & Rens, 2001; Sergeant & Welch, 2008), (e) patients with voice disorders (e.g., Prytz, 1978; Hartl, Hans, Vaissiere, & Brasnu, 2003) and (f) sexes and genders (e.g., Bladon, 1983; Klatt, 1986; Klatt, D. H. & Klatt, L. C., 1990; White, 2001).Therefore, collecting LTAS data for this particular study offered the opportunity to assess overall timbre and tone quality changes due to alterations in heel height.

I used KayPentax Computerized Speech Lab (CSL) Model 4500 software to assess long-term average spectra (LTAS) data, using a window size of 512 points with no pre-emphasis or smoothing, a Hamming window, and a bandwidth of 86.13 Hz. I obtained mean LTAS data of each harmonic on each vowel scale ([ɑ], [i]) from the two sung trials in each heel height to control for possible one-time variations.

Acoustical analysis 2: First formant frequency. The occurrence of fundamental frequencies close to or above the first formant frequency presents difficulties for voice research. First, linear predictive coding, commonly used to measure formant frequencies from spectrograms, tends to confuse the fundamental frequency with the first formant frequency. If the fundamental frequency exceeds 350 Hz, spectral analysis or linear predictive coding can become unreliable (Monsen & Engebretson, 1983). The frequency distance between spectrum harmonics becomes increasingly wider with an increase in fundamental frequency and can cause undersampling of the vocal tract transfer function in vocal sound, thus preventing the measurement of formant frequencies from an output signal (Deme, 2014).

Alternative methods for measuring formant frequencies have included using (a) low-frequency external vibrator excitation of the vocal tract (e.g., Sundberg, 1975; Joliveau, Smith, & Wolfe, 2004), (b) natural aperiodic source or glottal fry (e.g., Miller, Sulter, Schutte, & Wolf, 1997), (c) sliding pitches (e.g., White, 1999), (d) inverse filtering (e.g., Gauffin-Lindquist, 1964), (e) inverse filtering with electroglottograph signals (e.g., Rothenberg, 1979), (f) analysis by synthesis (e.g., Sundberg, 1975), (g)

MRI or radiographs (e.g., Johansson, Sundberg, & Wilbrand, 1982; Titze, Mapes, & Story, 1994; Sulter et al., 1992), and (h) mouth impedance with acoustic excitation (Kob & Neuschaefer-Rube, 2002). Unfortunately, these methods may (a) require specialized expensive equipment, (b) require participants to be supine, (c) expose participants to radiation, (d) lessen the ability to measure singers in a semi-naturalistic way, or (e) present problems with measurements (Erickson & D'Alfonso, 2002).

Therefore, this study examined the effects of formant frequency indirectly by examining whether participants significantly altered jaw opening and head position between fundamental frequencies below and above the juncture where the fundamental frequency would equal or exceed the first formant frequency of the low pitch of A3. Following Sundberg and Skoog (1997), I measured the first formant frequency of each vowel ([ɑ], [i]) on the lowest pitch of each scale (A3) and labeled this measurement $F_{1LowF0.}$ I accomplished this task by using Praat software (Boersma & Weenink, 2010) to computer linear predictive coefficients through the Burg algorithm integrated into the program, which applied a Gaussian-like window to extract the first formant frequency. I found the midpoint of the steady state vowel, and measured the midpoint plus .10 s on either side of the midpoint, which equaled a total selection of .20 s. I obtained a mean of all data points for F_{1LowF0} over the .20 s to account for possible changes in participant vibrato that could alter formant frequency measurements. Lastly, I averaged data from the two trials in each heel height condition to account for any one-time variations, which resulted in one F_{1LowF0} measurement for each vowel on the pitch of A3 in each heel height condition.

Using an online frequency to pitch converter (http://www.flutopedia.com/pitch_to_frequency.htm), I found the corresponding pitch where the fundamental frequency equaled or exceeded F_{1LowF0} for each vowel ([ɑ], [i]) in each heel height condition (0.0 in., 1.5 in., 3.0 in.). For example, I averaged all angle 1 head position measurements (HP 1) above the juncture where F_0 equaled or exceeded F_{1LowF0} (labeled as $\bar{X}_{PITCH>F1LOWF0}$) and averaged all angle 1 head position measurements below the juncture where F_0 equaled or exceeded F_{1LowF0} (labeled as $\bar{Y}_{PITCH<F1LOWF0}$). I repeated this same process for head position angle 2 measurements (HP 2) and jaw opening measurements (JO).

Acoustic analysis 3: dB SPL I employed a Praat software script (see Appendix E) (Boersma & Weenink, 2010) that trimmed each participant's 12 files (one for each scale and vowel in each heel height condition) by extracting sung segments and placing them into individual files by pitch. The script then calculated a mean of dB SPL from seconds 1.4 to 1.6 on each recording, which constituted the approximate midpoint of each 3 s sung pitch. After obtaining a mean of all data points for dB SPL over the .20 s to account for possible changes in participant vibrato that could alter amplitude, I averaged data from the two trials in each heel height condition to account for any one-time variations.

CHAPTER FOUR

Results

The purpose of this study was (a) to determine the effects, if any, of three simulated heel height conditions (0.0 in., 1.5 in., 3.0 in.) on postural (head position, jaw opening) and acoustical (LTAS, dB SPL) measures of university female voice majors (*N* = 35) in two conditions (silence, singing sustained [ɑ] and [i] vowels on each pitch of a two-octave A-major scale [A3-A5]), and then to (b) assess selected relationships between heel height behavior conditions, postural data, and acoustical data.

This chapter presents the results for this study in order of the stated research questions. A pre-determined alpha level of .05 served as an indication of significance for all statistical tests employed. I completed all statistical analyses using SPSS version 22.0 (SPSS, Inc.).

Research Question One: Head Position and Jaw Opening

Research question one inquired about potential significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from three heel height conditions (0.0 in., 1.5 in., 3.0 in.), two behavior conditions (silent, singing), two vowel conditions ([ɑ], [i]), and three pitch conditions (low [A3], medium [A4], and high [A5]). For this research question, I used postural measurements acquired from one pitch in each of three octaves (A3, A4, A5), rather than postural data from every pitch sung. I disaggregated participant data into columns (*N* = 54), labeled by “postural measurement, heel height, vowel, pitch” (e.g., HP 1, 0.0, ɑ, low), for input into SPSS software. I ran a 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA for each dependent postural measurement (HP 1, HP 2, JO).

For comparisons between silent and singing conditions, I used each participant's head position and jaw opening data from the silent condition and lowest sung pitch (A3) condition. I disaggregated data into columns ($N = 18$), labeled by "postural measurement, heel height, behavior" (e.g., HP 1, 0.0, silent), for input into SPSS software. I ran a 3x2 (heel height x behavior) repeated measures ANOVA for each dependent postural measurement (HP 1, HP 2, JO). Results are presented by each dependent postural variable.

Head position angle 1. Table 3 displays the means and standard deviations for participant head position angle 1 measurement data among each heel height, vowel, and pitch condition. Head position angle 1 measurements represented the amount of superior or inferior head movement. An increase in angle 1 measurements indicated a superior or elevated head movement; however, a decrease in angle 1 measurements indicated an inferior or lowered head movement.

Table 3

Means and Standard Deviations for Participant Head Position Angle 1 Measurements (degrees) Among Pitch, Vowel, and Heel Height Conditions

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
Silent	107.73	105.23	103.16	107.69	105.41	103.33
	5.46	*5.71*	*4.51*	*4.93*	*4.72*	*5.40*
A3	109.13	106.79	104.60	107.94	105.61	103.40
	4.82	*5.07*	*4.85*	*5.01*	*5.04*	*4.74*
B3	110.03	107.23	105.23	108.93	106.39	103.97
	4.54	*4.72*	*4.79*	*5.06*	*5.11*	*4.96*
C#4	109.81	107.73	105.34	108.96	106.26	104.20
	4.59	*4.37*	*4.63*	*5.11*	*4.96*	*4.86*
D4	110.00	107.83	105.66	109.09	107.04	104.50
	4.84	*4.40*	*4.31*	*5.51*	*5.08*	*5.05*
E4	110.21	108.01	105.54	109.13	106.69	104.84
	4.67	*4.53*	*4.38*	*5.29*	*5.09*	*5.06*

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
F#4	110.89	108.23	106.01	109.59	106.99	104.96
	4.65	*4.12*	*4.62*	*5.28*	*4.88*	*4.98*
G#4	110.89	108.33	106.26	109.29	106.97	105.01
	4.72	*4.45*	*4.50*	*5.04*	*5.00*	*5.25*
A4	111.19	108.64	106.59	109.64	107.33	105.14
	4.98	*4.57*	*4.87*	*5.32*	*4.64*	*4.73*
B4	111.00	108.53	106.41	109.84	107.41	105.36
	5.23	*5.10*	*4.73*	*5.14*	*4.97*	*4.90*
C#5	110.87	108.73	106.57	109.94	107.56	105.76
	5.72	*4.99*	*4.91*	*5.29*	*4.93*	*5.05*
D5	111.67	108.87	106.64	110.43	107.79	105.94
	5.06	*4.97*	*4.85*	*5.16*	*5.16*	*4.67*
E5	112.24	109.31	107.33	110.96	108.43	106.49
	5.14	*5.10*	*5.06*	*5.10*	*4.79*	*4.84*
F#5	112.49	110.07	106.44	111.54	109.04	106.94
	5.47	*4.92*	*4.91*	*5.01*	*5.13*	*5.02*
G#5	113.19	110.47	108.24	112.11	109.61	107.27
	5.55	*5.52*	*5.14*	*5.67*	*5.17*	*5.14*
A5	113.60	111.16	109.04	112.56	110.13	108.21
	5.69	*5.38*	*5.50*	*5.87*	*5.40*	*5.50*
Mean (A3-A5)	111.15	108.66	106.48	110.00	107.55	105.47
	4.70	*4.47*	*4.48*	*4.90*	*4.70*	*4.61*

Note. This table includes data from all pitches for descriptive purposes; however, only data from the pitches A3, A4, and A5 were used for purposes of statistical analyses.

A 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA found no significant interactions, all $F \leq 1.943$, $p \geq .159$, $\eta_p^2 \leq .105$. Mauchly's test indicated that the assumption of sphericity had been violated for the independent variable of pitch ($\chi^2(2) = 9.177$, $p = .010$). I therefore corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .839$). Results indicated a significant main effect for pitch, $F(1.677, 57.024) = 30.653$, $p < .001$, $\eta_p^2 = .474$, which indicated that participants, on average, increased head position angle 1 measurements (superior movement of the head) as they ascended the scale across low ($M = 106.25$ degrees), medium ($M = 108.09$ degrees), and high ($M = 110.78$ degrees) pitch conditions.

Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant head position angle 1 measurements across low (A3), medium (A4), and high (A5) pitch conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Results indicated significant differences in head position angle 1 measurements between all pitch conditions ($p < .001$).

Results also indicated a significant main effect for vowel, $F(1, 34) = 22.115$, $p < .001$, $\eta_p^2 = .394$. Participants, on average, increased head position angle 1 measurements (superior movement of the head) when singing on the vowel [ɑ] ($M = 108.97$ degrees) compared to the vowel [i] ($M = 107.78$ degrees).

A significant main effect of heel height, $F(2, 33) = 218.855$, $p < .001$, $\eta_p^2 = .930$, indicated that participants, on average, decreased head position angle 1 measurements (inferior movement of the head) as heel height increased from 0.0 in. ($M = 110.68$ degrees) to 1.5 in. ($M = 108.28$ degrees) to 3.0 in. ($M = 106.16$ degrees). Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant head position angle 1 measurements across heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Results indicated significant differences in head position angle 1 measurements between all heel height conditions ($p < .001$).

From silent to singing conditions, a 3x2 (heel height x behavior) repeated measures ANOVA found significant main effects for heel height, $F(2, 33) = 129.218$, $p < .001$, $\eta_p^2 = .887$, and behavior, $F(1, 34) = 7.119$, $p = .012$, $\eta_p^2 = .173$. Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant head position angle 1 measurements across heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/3 = .017$). Results indicated significant differences in head position angle 1 measurements between all heel height conditions ($p < .001$) when data were collapsed across behavior conditions. Participants decreased mean head position angle 1 measurements as heel height increased across 0.0 in. (M = 108.12 degrees), 1.5 in. (M = 105.76 degrees), and 3.0 in. (M = 103.62 degrees) heel conditions. Participants, on average, also increased angle 1 head position measurements from the silent condition (M = 105.42 degrees) to singing condition (M = 106.25 degrees). Results indicated no significant interactions.

Head position angle 2. Table 4 displays the means and standard deviations for participant head position angle 2 measurement data among each heel height, vowel, and pitch condition. Head position angle 2 measurements represented the amount of anterior or posterior head and neck movement. An increase in angle 2 measurements indicated an anterior or forward movement of the head and neck. A decrease in angle 2 measurements signified a posterior or backward movement of the head and neck.

Table 4

Means and Standard Deviations for Participant Head Position Angle 2 Measurements (degrees) Among Pitch, Vowel, and Heel Height Conditions

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
Silent	48.36	46.29	44.66	48.46	46.09	44.70
	5.94	*5.77*	*5.75*	*6.25*	*5.79*	*5.64*
A3	49.09	46.89	45.53	48.89	46.19	45.09
	5.84	*5.57*	*5.37*	*6.54*	*5.93*	*5.94*
B3	49.50	47.03	45.91	48.79	46.27	45.27
	5.67	*5.57*	*5.34*	*6.35*	*6.10*	*5.56*
C#4	49.43	47.24	45.61	48.63	46.16	45.19
	5.87	*5.30*	*5.43*	*6.29*	*6.00*	*5.66*
D4	49.73	47.20	45.90	48.51	46.30	45.10
	6.07	*5.63*	*5.62*	*6.21*	*6.21*	*5.81*
E4	49.91	47.44	46.11	48.91	46.40	45.41
	5.76	*5.67*	*5.53*	*6.70*	*6.70*	*5.89*

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
F#4	49.73	47.39	46.09	48.86	47.01	45.44
	6.09	*5.80*	*5.94*	*6.74*	*6.25*	*6.10*
G#4	49.77	47.59	46.21	49.33	47.04	45.73
	6.18	*5.64*	*5.91*	*6.26*	*6.50*	*5.86*
A4	49.93	47.99	46.51	49.51	47.29	45.80
	5.96	*5.67*	*5.54*	*6.43*	*6.36*	*6.19*
B4	50.29	48.16	46.53	49.54	47.39	46.10
	6.20	*5.73*	*5.95*	*6.75*	*6.56*	*5.87*
C#5	50.17	47.99	46.93	49.70	47.56	46.29
	6.45	*5.97*	*5.95*	*6.61*	*6.43*	*5.80*
D5	50.24	47.93	47.21	49.60	47.74	46.20
	6.48	*6.26*	*7.51*	*6.53*	*6.36*	*6.03*
E5	50.59	47.96	46.91	50.00	47.90	46.74
	6.40	*6.63*	*6.29*	*6.42*	*6.73*	*5.87*
F#5	50.60	48.09	47.17	50.11	47.90	46.76
	6.52	*6.61*	*6.20*	*6.85*	*6.59*	*6.06*
G#5	50.56	48.34	47.13	50.29	47.84	47.07
	6.68	*6.50*	*6.23*	*6.73*	*6.84*	*6.12*
A5	50.51	47.99	47.10	50.27	47.86	47.07
	6.86	*6.83*	*6.51*	*6.96*	*7.06*	*6.08*
Mean (A3-A5)	50.00	47.68	46.32	49.40	47.12	45.07
	6.09	*5.83*	*5.78*	*6.45*	*6.33*	*5.82*

Note. This table includes data from all pitches for descriptive purposes; however, only data from the pitches A3, A4, and A5 were used for purposes of statistical analyses.

A 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA found a significant main effect for vowel, $F(1, 34) = 8.071$, $p < .05$, $\eta_p^2 = .192$. Participants, on average, exhibited a slightly larger degree of angle 2 head position measurements (anterior movement of the head and neck) on the [ɑ] vowel ($M = 47.95$ degrees) compared to the [i] vowel ($M = 47.55$ degrees).

Results also indicated a significant main effect for heel height, $F(2, 33) = 143.036$, $p < .001$, $\eta_p^2 = .897$. Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant head position angle 2 measurements across heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$).

Results indicated significant differences in head position angle 2 measurements between all heel height conditions ($p < .001$). Participants, on average, decreased head position angle 2 measurements (posterior movement of the head and neck) as heel height increased across 0.0 in. ($M = 49.70$ degrees), 1.5 in. ($M = 47.36$ degrees), and 3.0 in. ($M = 46.18$ degrees) conditions.

Mauchly's test indicated that the assumption of sphericity had been violated for the independent variable of pitch ($\chi^2(2) = 11.767$, $p = .003$). I therefore corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .799$). The adjusted values indicated a significant main effect for pitch, $F(1.597, 54.306) = 11.980$, $p < .001$, $\eta_p^2 = .261$. Three follow-up paired *t*-tests (two-tailed) measured specific differences in participant head position angle 2 measurements among pitch conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Results indicated significant differences in head position angle 2 measurements between all pitch conditions ($p < .001$), with the exception of the comparison between medium (A4) and high (A5) pitches ($p = .044$). Participants tended to increase angle 2 head position measurements (anterior movement of the head and neck) as pitch ascended across low ($M = 46.94$ degrees), medium ($M = 47.84$ degrees), and high ($M = 48.47$ degrees) pitch conditions.

Of particular interest, the omnibus ANOVA found a significant interaction between pitch and heel height, $F(4, 31) = 3.817$, $p < .05$, $\eta_p^2 = .330$. Figure 13 displays the two-way interaction plot. Participants, on average, increased head position angle 2 measurements as pitch ascended. As heel height increased, participants decreased head position angle 2 measurements to a larger degree from the 0.0 in. to 1.5 in. conditions than from 1.5 in. to 3.0 in. conditions. Therefore, head position angle 2 measurements depended on both pitch and heel height conditions.

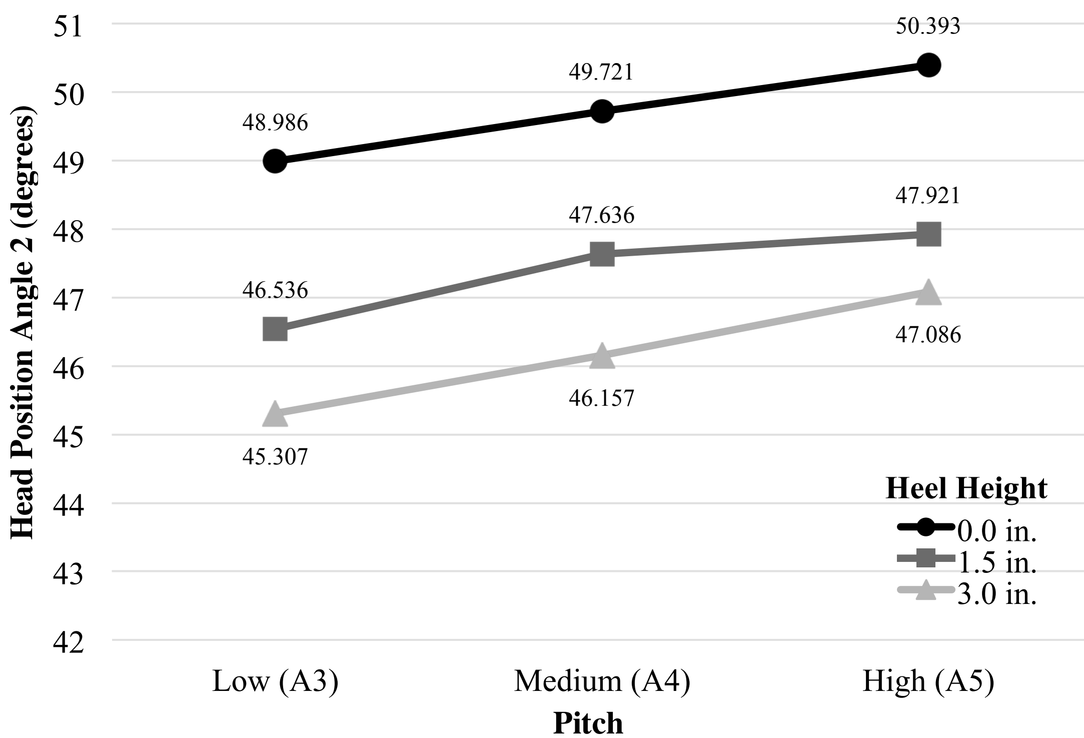

Figure 13. Head position angle 2 measurements interaction: Pitch by heel height.

From silent to singing conditions, a 3x2 (heel height x behavior) repeated measures ANOVA found significant main effects for heel height, $F(2, 33) = 131.648$, $p < .001$, $\eta_p^2 = .889$, and behavior, $F(1, 34) = 5.246$, $p = .028$, $\eta_p^2 = .134$. Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant head position angle 2 measurements collapsed across silent and singing conditions in each heel height with a Bonferroni adjustment of alpha levels ($p = .05/3 = .017$). Results indicated significant differences in head position angle 2 measurements between all heel height conditions ($p < .001$). Participants decreased mean head position angle 2 measurements as heel height increased across 0.0 in. ($M = 48.70$ degrees), 1.5 in. ($M = 46.36$ degrees), and 3.0 in. ($M = 44.99$ degrees) heels. Participants, on average, also increased angle 2 head position measurements from the silent condition (*M* = 46.42 degrees) to the low pitch (A3) singing condition (*M* = 46.94 degrees). Results indicated no significant interactions.

Jaw opening. Table 5 displays the means and standard deviations for participant jaw opening measurement data among each heel height, vowel, and pitch condition. An increase in jaw opening measurements indicated an increase in the opening of the buccal cavity and a lowering of the mandible, while a decrease indicated a smaller mouth opening and elevated mandible.

Table 5.

Means and Standard Deviations for Participant Jaw Opening Measurements (degrees) Among Pitch, Vowel, and Heel Height Conditions

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
Silent	57.90	55.70	55.24	58.19	56.41	55.03
	4.57	*3.88*	*4.49*	*4.67*	*4.04*	*4.24*
A3	64.99	62.74	61.27	60.61	58.03	57.04
	5.49	*4.70*	*4.63*	*4.54*	*4.16*	*4.00*
B3	65.90	62.64	61.56	60.77	58.40	57.41
	5.69	*4.81*	*4.76*	*4.79*	*4.64*	*4.21*
C#4	65.44	62.77	61.54	60.91	58.00	57.41
	6.20	*4.65*	*4.84*	*5.34*	*4.08*	*3.96*
D4	65.80	62.70	62.00	61.16	58.56	57.54
	5.92	*4.75*	*5.01*	*5.11*	*4.47*	*4.23*
E4	65.99	63.46	62.19	61.46	58.87	58.26
	5.76	*5.05*	*4.93*	*5.22*	*4.52*	*4.18*
F#4	66.54	63.53	62.33	61.83	59.27	58.30
	5.88	*5.22*	*5.26*	*5.25*	*4.07*	*3.66*
G#4	66.76	64.10	62.91	62.16	59.46	58.74
	6.12	*4.78*	*5.21*	*5.06*	*4.21*	*4.15*
A4	66.93	64.54	63.20	62.60	59.93	59.10
	5.96	*5.15*	*5.39*	*5.12*	*4.38*	*4.38*
B4	67.03	64.79	63.13	62.99	60.36	59.84
	5.84	*5.47*	*4.95*	*5.19*	*4.96*	*4.63*
C#5	67.03	64.53	63.46	63.99	61.11	60.66
	6.04	*5.27*	*5.22*	*5.29*	*4.83*	*4.57*

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
D5	67.44	64.53	63.54	64.33	61.93	61.14
	6.02	*4.99*	*5.46*	*5.45*	*4.57*	*4.80*
E5	68.53	65.31	64.54	66.20	63.51	63.07
	6.10	*4.71*	*5.41*	*5.33*	*4.94*	*5.16*
F#5	69.74	66.63	65.74	67.86	64.91	64.69
	6.62	*5.58*	*5.32*	*5.97*	*4.92*	*5.48*
G#5	71.31	68.81	67.67	69.77	67.07	66.43
	6.38	*5.61*	*5.32*	*6.55*	*5.97*	*5.30*
A5	72.93	69.79	69.07	71.14	68.63	68.06
	6.63	*5.58*	*5.68*	*6.65*	*6.12*	*5.70*
Mean (A3-A5)	67.49	64.72	63.61	63.85	61.20	60.06
	5.76	*4.85*	*4.93*	*5.14*	*4.44*	*4.30*

Note. This table includes data from all pitches for descriptive purposes; however, only data from the pitches A3, A4, and A5 were used for purposes of statistical analyses.

A 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA found a significant main effect for heel height, $F(1.742, 59.237) = 71.103$, $p < .001$, $\eta_p^2 = .677$. Mauchly's test indicated that the assumption of sphericity had been violated for the independent variable of heel height ($\chi^2(2) = 7.364$, $p = .025$). I therefore corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .871$). Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant jaw opening measurements across heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Results indicated significant differences in jaw opening measurements between all heel height conditions ($p < .001$). Participants, on average, decreased jaw opening as heel height increased (0.0 in. [M = 66.53 degrees], 1.5 in. [M = 63.94 degrees], and 3.0 in. [M = 62.96 degrees]).

Results indicated a significant main effect for vowel, $F(1, 34) = 124.183$, $p < .001$, $\eta_p^2 = .785$. Participants, on average, increased jaw opening while singing the vowel [ɑ] (M = 66.16 degrees) compared to the vowel [i] (M = 62.79 degrees).

Results also denoted a main effect for pitch, $F(1.211, 41.161) = 180.190$, $p < .001$, $\eta_p^2 = .841$. Mauchly's test indicated that the assumption of sphericity had been violated for the independent variable of pitch ($\chi^2(2) = 34.839$, $p < .001$). Therefore, I corrected degrees of freedom using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .605$). Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant jaw opening measurements across pitch conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Results indicated significant differences in jaw opening measurements between all pitch conditions ($p < .001$). Participants, on average, tended to increase jaw opening measurements as pitch ascended across low ($M = 60.78$ degrees), to medium ($M = 62.71$ degrees), to high ($M = 69.94$ degrees) pitches.

Of particular interest, the omnibus ANOVA found a significant interaction between pitch and vowel, $F(2, 33) = 37.664$, $p < .001$, $\eta_p^2 = .695$. Figure 14 displays the interaction plot between pitch and vowel conditions. Participants, on average, increased jaw opening as pitch ascended. Participants exhibited a greater amount of jaw opening when singing the vowel [ɑ] compared to the vowel [i]. However, the mean difference between singer jaw opening on [ɑ] compared to [i] decreased as pitch ascended across low pitch (*M* difference = 4.44 degrees), medium pitch (*M* difference = 4.35 degrees), and high pitch (*M* difference = 1.32 degrees) conditions, which indicated a similar degree of singer jaw opening, regardless of vowel, on the high pitch of A5.

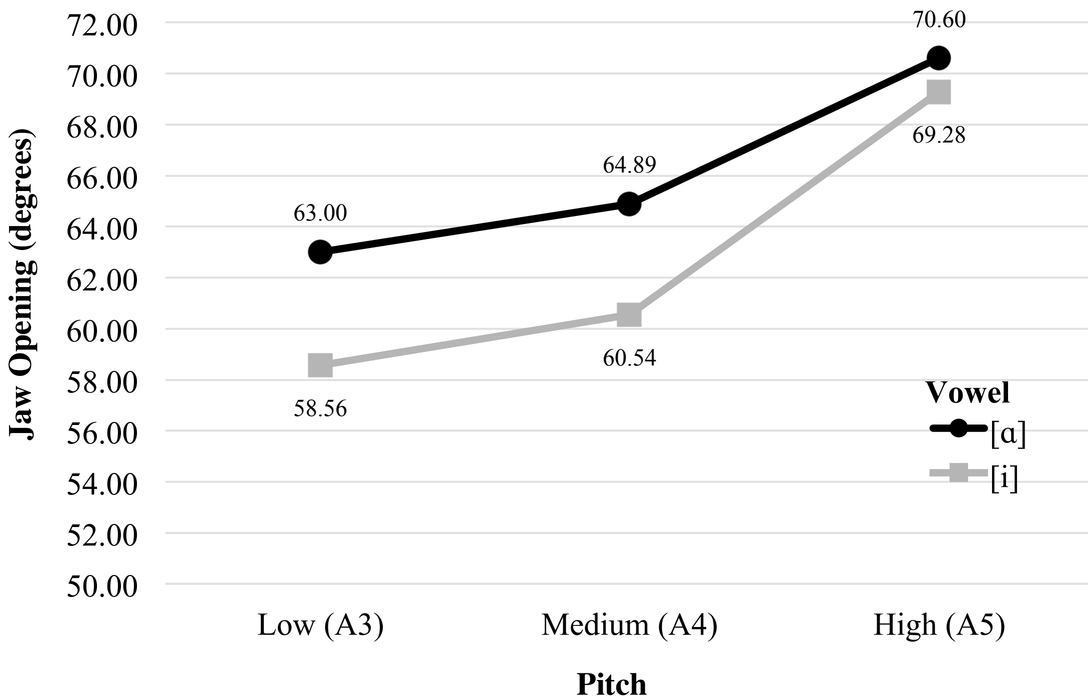

Figure 14. Jaw opening measurements interaction: Pitch by vowel.

From silent to singing conditions, a 3x2 (heel height x behavior) repeated measures ANOVA found significant main effects for heel height, $F(1.615, 54.895) = 55.229$, $p < .001$, $\eta_p^2 = .716$, and behavior, $F(1, 34) = 184.965$, $p = < .001$, $\eta_p^2 = .845$. For the independent variable of heel height, Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(2) = 11.167$, $p = .004$). I therefore corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .807$). Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant jaw opening measurements across heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/3 = .017$). Results indicated significant differences in jaw opening measurements between all heel height conditions ($p < .001$). Participants gradually decreased jaw opening measurements across 0.0 in. ($M = 60.42$ degrees), 1.5 in. ($M = 58.22$ degrees), and 3.0 in. ($M = 57.15$ degrees) heel height conditions. Participants also exhibited a greater amount of jaw opening when singing the low pitch of A3 (M = 60.78 degrees) compared to the silent condition (M = 56.41 degrees).

Results indicated a significant interaction between heel height and behavior, $F(2, 33) = 3.642$, $p = .037$, $\eta_p^2 = .181$. Figure 15 displays a plot of the interaction between heel height and behavior. The interaction between heel height and behavior signified that the difference in participant jaw opening could not be accounted for by heel height or behavior independently. As heel height increased, participants, on average, decreased jaw opening. From silent to singing conditions, participants, on average, increased jaw opening. However, the amount of increased jaw opening from silent to singing conditions decreased as heel height increased among 0.0 in. (M difference = 4.76 degrees), 1.5 in. (M difference = 4.35 degrees), and 3.0 in. (M difference = 4.02 degrees) heel height conditions.

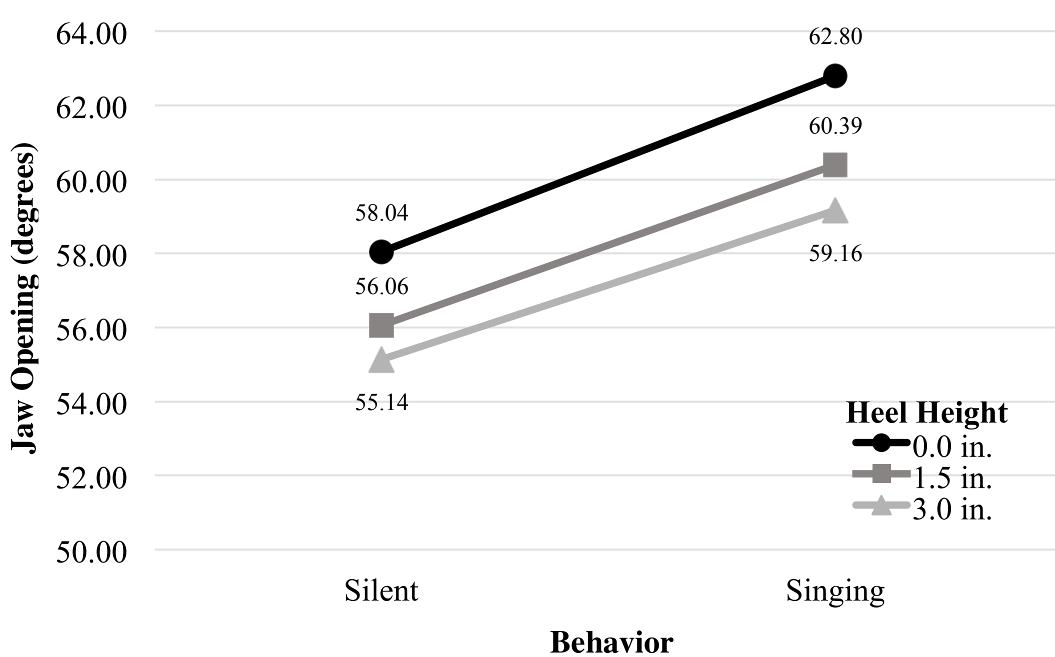

Figure 15. Jaw opening measurements interaction: Behavior by heel height.

Research Question Two: LTAS

Howard and Angus (2001) stated that a 1 dB difference in the signal energy of a complex sound constituted a just noticeable difference in the perception of vocal timbre. Therefore, any differences of 1 dB or greater will be important in consideration of the following results.

Research question two asked if there were statistically significant differences among LTAS data (0 – 10 kHz) acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.) and (b) two vowel conditions ([ɑ], [i]). For each individual participant, I averaged the LTAS data of each harmonic across two trials in order to account for any one-time variations. In order to test for differences in grand mean harmonic amplitude across all participants, I averaged each harmonic (0 – 10 kHz, $N = 117$) for each heel height and vowel condition across all participants and disaggregated data into columns ($N = 6$) labeled by "heel height, vowel" (e.g., 0.0, ɑ), for entry into SPSS. Therefore, the statistical tests for LTAS data represented whether or not the amplitude of each harmonic significantly differed between heel height and vowel conditions.

A 3x2 (heel height x vowel) repeated measures ANOVA found a significant main effect for heel height, $F(1.326, 153.772) = 112.789$, $p < .001$, $\eta_p^2 = .493$. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(2) = 81.737$, $p < .001$). I therefore corrected degrees of freedom using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .663$). Three follow-up paired *t*-tests (two-tailed) measured specific differences in mean participant LTAS data between heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/3 = .017$). Results indicated significant differences in LTAS data between all heel height conditions ($p < .001$). Participants, on average, exhibited a slightly greater mean signal energy in the 0.0 in. heel height condition (*M* = 28.66 dB SPL, *SD* = 11.42 dB SPL) than in the 1.5 in. (*M* = 28.61 dB SPL, *SD* = 11.39 dB SPL) and 3.0 in. (*M* = 28.59 dB SPL, *SD* = 11.38 dB SPL) heel conditions. That is, as heel height increased, mean signal energy decreased slightly.

Results did not indicate a significant main effect for vowel. However, there was a significant interaction between heel height and vowel, $F(1.702, 197.477) = 143.308$, $p < .001$, $\eta_p^2 = .553$. Figure 16 displays the interaction plot between heel height and vowel for LTAS data. Mauchly's test revealed that the assumption of sphericity had been violated for this interaction ($\chi^2(2) = 24.252$, $p < .001$). Therefore, I corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .851$). This interaction signified that neither vowel nor heel height alone informed LTAS data. Overall participant mean LTAS data indicated that signal energy increased when participants sang the vowel [i] (*M* = 28.69 dB SPL, *SD* = 10.94 dB SPL) compared to the vowel [ɑ] (*M* = 28.55 dB SPL, *SD* = 12.26 dB SPL) and decreased as heel height increased. However, while participants' sung [i] vowels exhibited most energy during the 3.0 in. heel condition (*M* = 28.71 dB SPL, *SD* = 10.92 dB SPL), participants' sung [ɑ] vowels exhibited most energy during the 0.0 in. heel condition (*M* = 28.63 dB SPL, *SD* = 12.30 dB SPL).

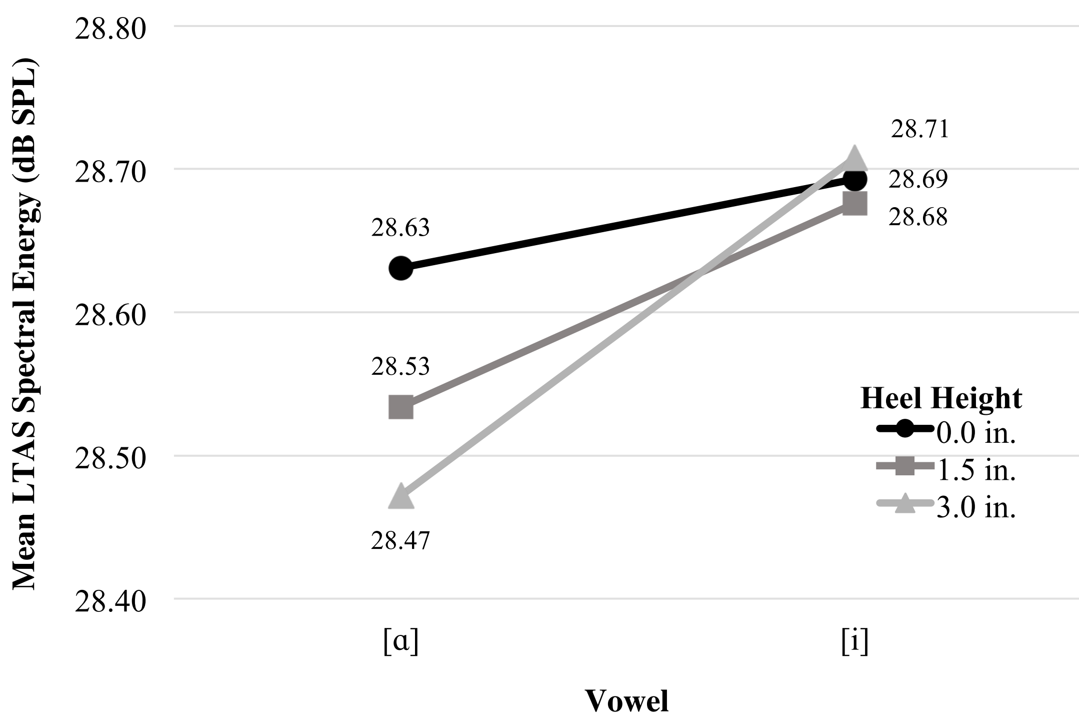

Figure 16. LTAS mean signal energy interaction: Vowel by heel height.

Differences in mean signal LTAS data for these participants across heel height conditions, on average, did not yield differences greater than 1 dB. However, from the 0.0 in. heel height to the 3.0 in. heel height condition, every harmonic decreased, some as much as 0.50 dB, and some individual participants exhibited differences in mean signal LTAS energy greater than 1 dB.

Research Question Three: dB SPL

Research question three asked if there were statistically significant dB SPL (0 – 10 kHz) measurement differences acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), two vowel conditions ([ɑ], [i]), and (c) low, medium, high pitch conditions (A3, A4, A5). For analysis purposes, I limited the factor of pitch to three levels and used the dB SPL measurements from A3 (low), A4 (middle), and A5 (high) pitches for each participant. I disaggregated data into columns (N = 18) labeled by "heel height, vowel, pitch" (e.g., 0.0, ɑ, low), for input into SPSS. I ran a 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA to test for differences in dB SPL data between heel height, vowel, and pitch.

Table 6 displays the means and standard deviations for participant dB SPL data acquired from each heel height, vowel, and pitch condition.

Table 6

Means and Standard Deviations for Participant Intensity Measurements (dB SPL) Among Pitch, Vowel, and Heel Height Conditions

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
A3	86.83	87.14	87.42	82.98	82.96	83.19
	9.68	*9.55*	*9.59*	*2.68*	*2.78*	*2.60*
B3	89.73	89.77	89.78	94.65	84.79	84.76
	9.86	*9.75*	*9.62*	*2.67*	*2.86*	*2.66*
C#4	90.89	91.06	91.04	97.56	87.70	87.80
	9.69	*9.62*	*9.62*	*3.10*	*2.97*	*2.99*
D4	91.87	97.76	91.70	88.84	88.70	88.73
	9.73	*9.88*	*9.94*	*3.37*	*3.00*	*3.14*
E4	93.94	93.75	93.87	91.77	92.06	94.16
	10.43	*10.39*	*10.37*	*3.58*	*3.45*	*3.23*
F#4	95.73	95.73	95.75	94.30	94.68	94.73
	10.60	*10.23*	*10.40*	*3.63*	*3.55*	*3.44*
G#4	97.40	97.39	97.36	97.12	97.23	97.20
	9.99	*9.96*	*9.65*	*3.40*	*3.44*	*3.25*
A4	97.90	97.88	97.97	99.22	99.48	99.36
	10.08	*10.10*	*9.77*	*3.65*	*3.42*	*3.33*
B4	99.25	99.32	99.31	101.98	102.30	102.15
	11.37	*11.06*	*11.19*	*3.78*	*3.60*	*3.48*
C#5	102.47	102.41	102.62	104.86	105.24	105.20
	12.39	*12.27*	*12.30*	*3.89*	*3.69*	*3.66*
D5	105.05	104.88	105.40	106.96	107.08	106.91
	13.15	*12.78*	*12.91*	*4.26*	*3.96*	*4.15*
E5	108.82	109.14	109.20	109.61	109.74	109.79
	14.14	*13.93*	*14.23*	*4.43*	*4.27*	*4.36*
F#5	111.75	111.87	111.84	112.13	112.17	112.26
	14.28	*14.28*	*14.51*	*4.65*	*4.61*	*4.77*
G#5	113.73	113.94	113.89	114.31	114.60	114.38
	13.91	*14.11*	*14.22*	*4.82*	*4.77*	*4.97*

Vowel	[ɑ]			[i]		
Heel Height	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
A5	114.81	114.84	114.79	114.88	115.40	115.37
	13.39	*13.81*	*13.69*	*4.88*	*4.82*	*4.69*
Mean	100.01	100.06	100.13	99.41	99.61	99.60
	8.75	*8.78*	*8.76*	*10.49*	*10.56*	*10.50*

Note. This table includes data from all pitches for descriptive purposes; however, only data from the pitches A3, A4, and A5 were used for purposes of statistical analyses.

A 3x2x3 (heel height x vowel x pitch) repeated measures ANOVA found a significant main effect for the independent variable of heel height, $F(2, 33) = 3.451$, $p = .044$, $\eta_p^2 = .173$. Three follow-up paired *t*-tests (two-tailed) measured specific differences in participant dB SPL data between heel height conditions with a Bonferroni adjustment of alpha levels ($p = .05/6 = .008$). Due to the adjusted alpha level to account for Type 1 error, results indicated no significant differences in dB SPL data between heel height conditions (0.0 in. to 1.5 in. [$p = .092$], 1.5 in. to 3.0 in. [$p = .448$], and 0.0 in. to 3.0 in. [$p = .012$]). Participants, on average, sang with more energy in the 3.0 in. heel height condition ($M = 57.68$ dB SPL, $SD = 2.91$ dB SPL) than in the 1.5 in. ($M = 57.62$ dB SPL, $SD = 57.62$ dB SPL) and 0.0 in. ($M = 57.44$ dB SPL, $SD = 2.95$ dB SPL) conditions.

Results indicated a significant main effect for the variable of vowel, $F(1, 34) = 13.479$, $p = .001$, $\eta_p^2 = .284$. On average, participants sang with greater amplitude on the vowel [ɑ] ($M = 57.95$ dB SPL, $SD = 3.06$ dB SPL) than on the vowel [i] ($M = 57.20$ dB SPL, $SD = 2.90$ dB SPL).

Mauchly's test revealed that the assumption of sphericity had been violated for the independent variable of pitch ($\chi^2(2) = 13.982$, $p = .001$). I therefore corrected degrees of freedom using Huynh-Feldt estimates of sphericity ($\varepsilon = .769$). Results revealed a significant main effect for pitch, $F(1.539, 52.317) = 982.089$, $p < .001$, $\eta_p^2 = .967$. Three follow-up paired *t*-tests (two-tailed) measured specific differences between participant dB SPL data across pitch conditions with a Bonferroni adjustment of alpha levels (p = .05/6 = .008). Results indicated significant differences in mean participant amplitude (dB SPL) between all three measured pitch conditions (p < .001). Participants sang with the most amplitude on the higher pitch of A5 (M = 73.02 dB SPL, SD = 4.93 dB SPL), followed by the medium pitch of A4 (M = 56.64 dB SPL, SD = 2.95 dB SPL), and finally the low pitch of A3 (M = 43.09 dB SPL, SD = 2.92 dB SPL).

The omnibus ANOVA found a significant interaction between vowel and pitch, $F(1.316, 44.732) = 44.258$, $p < .001$, $\eta_p^2 = .566$. Figure 17 displays the interaction plot between vowel and pitch and their relationship to dB SPL. Mauchly's test revealed that the assumption of sphericity had been violated for this interaction ($\chi^2(2) = 24.233$, $p < .001$). I therefore corrected degrees of freedom using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .658$). The interaction indicated that the variance in participant dB SPL measurements could not be explained by pitch or vowel alone. While participants, on average, increased amplitude as pitch ascended, and sang with greater amplitude on the vowel [ɑ] compared to the vowel [i], these two independent variables interacted together to elicit differences in the dependent variable of dB SPL. Participants singing the low pitch of A3 sang with more amplitude on the vowel [ɑ] (M = 45.13 dB SPL, SD = 3.62 dB SPL) than on the vowel [i] (M = 41.04, dB SPL, SD = 2.66 dB SPL) with a mean difference of 4.09 dB SPL. When participants sang the medium pitch of A4, participants sang with the most amplitude on the vowel [i] (M = 57.35 dB SPL, SD = 3.44 dB SPL) compared to the vowel [ɑ] (M = 55.92 dB SPL, SD = 3.42 dB SPL) with a mean difference of 1.43 dB SPL. When singing the high pitch of A5, participants sang with the most amplitude on the vowel [i] (*M* = 73.22 dB SPL, *SD* = 4.76 dB SPL) compared to the vowel [ɑ] (*M* = 72.82 dB SPL, *SD* = 5.13 dB SPL) with a mean difference of 0.4 dB SPL. Therefore, (a) participants, on average, exhibited a greater mean difference in amplitude (dB SPL) between vowels on the low pitch of A3 compared to the high pitch of A5, and (b) sang with greater amplitude on the [ɑ] vowel on a low pitch, but sang with greater amplitude on the [i] vowel on both the medium and high pitches. Results indicated no other significant interactions.

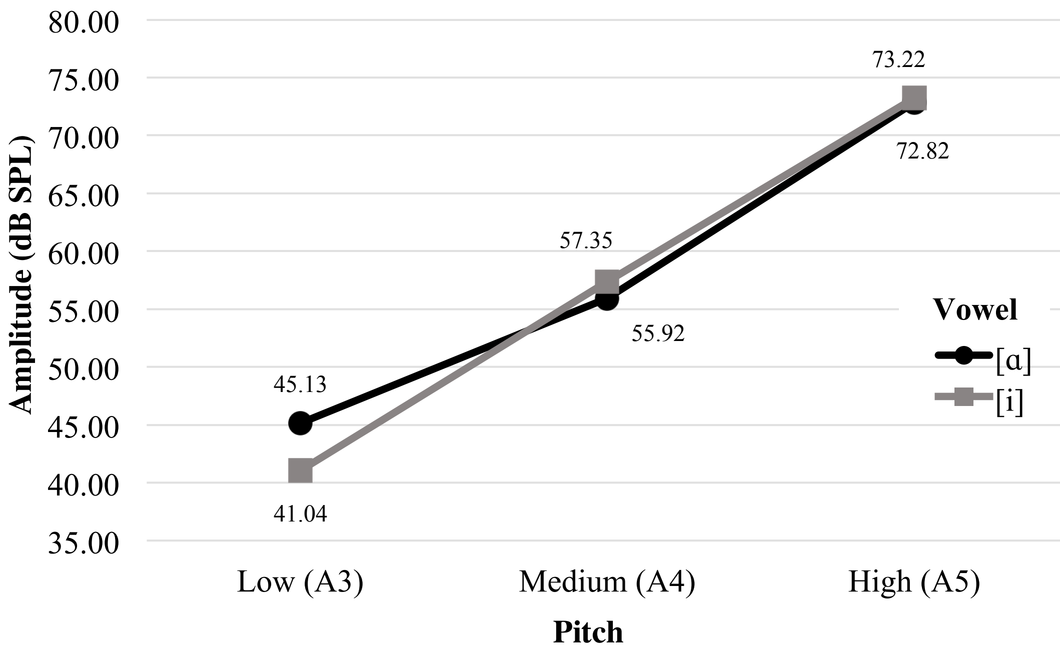

Figure 17. dB SPL measurements interaction: Pitch by vowel.

Research Question Four: $\overline{X}_{PITCH>F1LOWF0}$ and $\overline{Y}_{PITCH<F1LOWF0}$

Research question four inquired about potential significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from three heel height conditions (0.0 in., 1.5 in., 3.0 in.) and two vowel conditions ([ɑ], [i]), after disaggregating and averaging data for each dependent variable into levels of

$\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0}). In order to locate the pitch where the first formant frequency would equal or exceed the fundamental frequency, I measured the first formant frequency of the low pitch of A3 for each participant as she sang each scale two times on the vowel [ɑ] and two times on the vowel [i] in three different heel height conditions. I obtained a mean of each individual participant's formant frequency data across the two trials to account for possible one-time variations. After I calculated mean formant frequency data across all participants for each heel height and vowel condition, I used an online calculator to determine the approximate pitch of the formant frequency (http://www.flutopedia.com/pitch_to_frequency.htm). Table 7 displays the formant frequency data for all participants and the corresponding pitch where the first formant frequency would equal or exceed the fundamental frequency.

Table 7

Participant First Formant Frequency Measurements (Hz) of the Low Pitch A3 for Vowel and Heel Height Conditions and Corresponding Pitches

Vowel	[ɑ]			[i]		
Participant	0.0 in.	1.5 in.	3.0 in.	0.0 in.	1.5 in.	3.0 in.
1	787.27	762.97	737.23	414.49	405.96	398.60
2	728.80	726.94	728.21	321.97	305.83	311.49
3	685.70	677.00	665.88	314.80	333.23	342.50
4	742.68	743.05	758.12	408.66	403.29	401.80
5	686.72	696.33	702.09	362.01	366.84	358.92
6	735.49	722.65	752.02	405.55	402.12	403.09
7	814.94	771.92	764.83	305.86	318.05	297.86
8	671.60	625.99	663.69	297.52	283.83	283.81
9	784.49	764.50	712.66	270.87	273.69	284.51
10	637.26	645.31	641.71	352.81	351.84	351.40
11	671.34	665.08	641.64	366.74	369.51	376.23
12	754.46	745.44	762.37	399.97	391.72	408.25
13	667.65	663.60	663.90	334.50	349.31	349.91

14	669.13	670.17	664.00	349.77	360.55	361.96
15	688.98	684.73	668.61	313.96	324.31	325.40
16	748.42	771.37	735.97	340.22	330.30	342.01
17	634.40	650.17	654.86	367.75	349.49	308.83
18	766.12	769.58	795.98	375.44	355.68	341.05
19	673.60	653.70	651.81	394.88	385.30	367.48
20	702.55	756.59	700.22	398.14	396.03	415.15
21	641.01	589.24	640.40	352.58	341.88	332.04
22	712.71	730.41	684.25	282.76	282.45	276.45
23	698.77	692.07	701.75	351.61	335.27	326.86
24	660.43	648.57	649.75	266.07	269.05	265.44
25	733.32	732.45	697.70	271.13	284.47	293.54
26	766.92	795.60	764.03	376.05	371.60	375.21
27	823.12	797.23	821.36	417.36	411.29	427.63
28	693.23	693.55	659.04	418.58	417.16	424.46
29	637.10	709.29	671.90	315.70	310.61	321.42
30	693.65	685.69	680.67	367.91	335.05	318.23
31	608.07	611.57	629.20	302.91	300.23	299.87
32	685.11	729.87	670.12	388.38	399.54	395.12
33	743.96	730.02	744.40	377.66	377.08	362.81
34	770.25	733.76	750.20	333.54	328.12	314.17
35	670.93	671.43	733.35	408.31	411.90	407.55
Mean	708.29	706.22	701.82	352.18	349.50	347.74
SD	*53.85*	*52.86*	*49.60*	*45.60*	*43.82*	*45.97*
Corresponding Pitch	F#5	F#5	F#5	F#4	F#4	F#4

Results indicated that participants, on average, decreased the first formant frequency on the pitch A3 as heel height increased. As expected, participants also exhibited a higher first formant frequency on the vowel [ɑ] than on the vowel [i]. The approximate pitch locations for the first formant frequencies corresponded to F#5 for the vowel [ɑ] and F#4 for the vowel [i] of the two-octave A-major scales participants sang.

I then obtained mean postural data for each dependent variable (HP 1, HP 2, JO) in each vowel condition ([ɑ], [i]) and each heel height condition (0.0 in., 1.5 in., 3.0 in.) for all pitches higher than F_{1LowF0} (labeled $\bar{X}_{PITCH>F1LOWF0}$) and all pitches lower than F_{1LowF0} (labeled $\bar{Y}_{PITCH<F1LOWF0}$). I disaggregated data into columns (N = 12) labeled by

“heel height, vowel, formant location“ (e.g., 0.0, ɑ, $\bar{X}_{PITCH>F1LOWF0}$; 0.0, ɑ, $\bar{Y}_{PITCH<F1LOWF0}$). I performed a 3x2x2 (heel height x vowel x formant location) repeated measures ANOVA for each dependent postural measurement (HP 1, HP 2, JO).

Head position angle 1. A 3x2x2 (heel height x vowel x formant location) repeated measures ANOVA found no significant interactions, all $F \leq 7.450$, $p \geq .010$, $\eta_p^2 \leq .180$. Results indicated a significant main effect for heel height, $F(2, 33) = 201.732$, $p < .001$, $\eta_p^2 = .924$, and vowel, $F(1, 34) = 49.214$, $p < .001$, $\eta_p^2 = .591$. However, because information obtained by a significant main effect implied collapsed data across all other variables, this information duplicated the findings of research question one and thus will not be presented here.

A significant main effect of formant location, $F(1, 34) = 28.042$, $p < .001$, $\eta_p^2 = .452$, indicated that participants, on average, sang with a greater amount of superior head elevation ($M = 109.47$ degrees, $SD = 4.88$ degrees) on pitches above the point where $F0 > F_{1LOWF0}$ compared to pitches below the point where $F0 > F_{1LOWF0}$ ($M = 107.38$ degrees, $SD = 4.57$ degrees) regardless of heel height or vowel.

Head position angle 2. A 3x2x2 (heel height x vowel x formant location) repeated measures ANOVA found significant main effects for heel height, $F(2, 33) = 177.634$, $p < .001$, $\eta_p^2 = .915$, and vowel, $F(1, 34) = 45.645$, $p < .001$, $\eta_p^2 = .573$. However, as mentioned previously, because a main effect collapses across all other variables, this information duplicated results from the first research question and will not be presented again here.

Results indicated a significant main effect for formant location, $F(1, 34) = 18.363$, $p < .001$, $\eta_p^2 = .351$, which suggested that participants increased angle 2 head position measurements (anterior movement of the head and neck) on pitches above the point where F0>F_{1LOWF0} (*M* = 48.24 degrees, *SD* = 6.36 degrees) compared to pitches below the point where the F0>F_{1LOWF0} (*M* = 47.32 degrees, *SD* = 5.87 degrees).

Interestingly, the omnibus ANOVA for head position angle 2 measurements found a significant three-way interaction between heel height, vowel, and formant location, $F(2, 33) = 3.527$, $p = .041$, $\eta_p^2 = .176$. Participants, on average, exhibited an increase in head position angle 2 measurements regardless of vowel or heel height on pitches above the point where the fundamental frequency would equal or exceed the F_{1LOWF0}, compared to pitches below the point where the fundamental frequency would equal or exceed the F_{1LOWF0}. Participants, on average, exhibited an increase in head position angle 2 measurements regardless of heel height or formant location when singing the vowel [ɑ] compared to the vowel [i]. Participants, on average, exhibited a decrease in head position angle 2 measurements regardless of vowel or formant location as heel height increased.

However, the three-way interaction between heel height, vowel, and formant location suggested that one or more two-way interactions differed across the levels of a third variable. Figure 18 displays the interaction of vowel and heel height within the first level of formant location ($\bar{X}_{PITCH>F1LOWF0}$), i.e., the mean data for head position angle 2 measurements on pitches above the point where the fundamental frequency would equal or exceed the first formant frequency. Figure 19 displays the interaction of vowel and heel height within the second level of formant location ($\bar{Y}_{PITCH<F1LOWF0}$), i.e., the mean data for head position angle 2 measurements on pitches below the point where the fundamental frequency would equal or exceed the first formant frequency. These

interaction plots indicated greater mean differences in head position angle 2 measurements between vowel conditions as heel height increased on pitches below the point where the fundamental frequency would equal or exceed the first formant frequency. For head position angle 2 measurements above the point where the fundamental frequency would equal or exceed the first formant frequency, the mean differences in data between vowel conditions as heel height increased appeared to be attenuated, although still present, perhaps suggesting some degree of vowel modification based on formant tuning across heel height conditions.

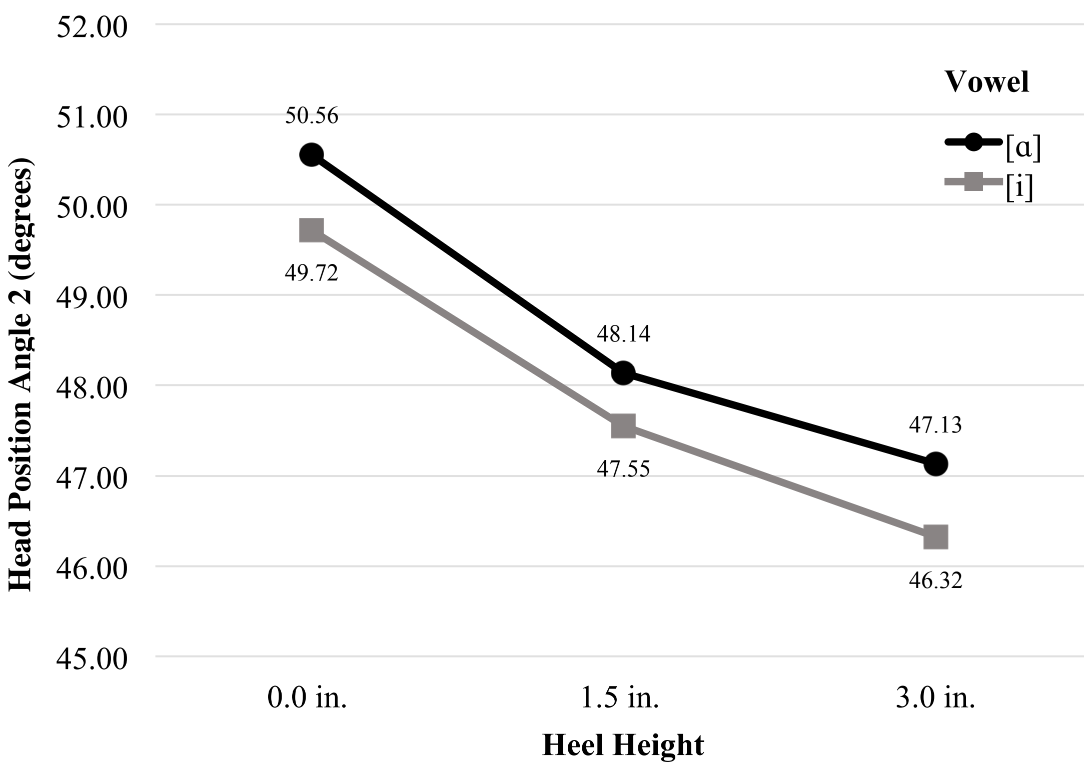

Figure 18. Head position angle 2 measurements three-way interaction: Heel height by vowel within the first level of formant location ($\bar{X}_{\text{PITCH>F1LOWF0}}$).

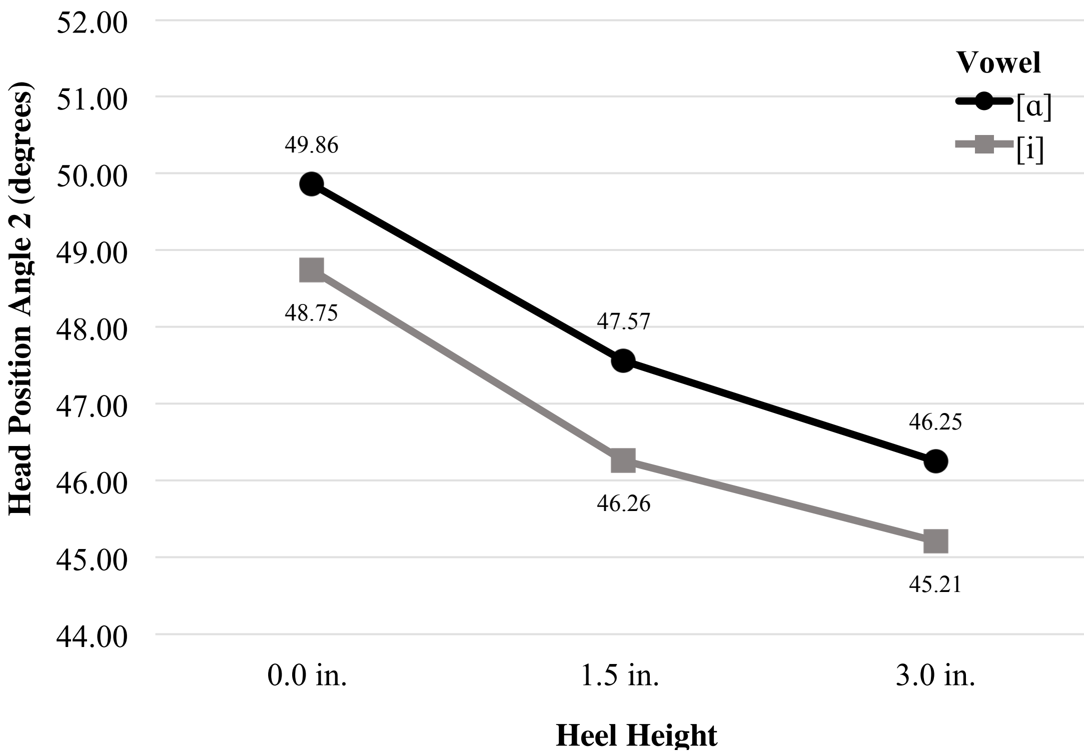

Figure 19. Head position angle 2 measurements three-way interaction: Heel height by vowel within the second level of formant location ($\bar{Y}_{\text{PITCH<F1LOWF0}}$).

Jaw opening. A 3x2x2 (heel height x vowel x formant location) repeated measures ANOVA found no significant interactions, all $F \leq 1.857$, $p \geq .172$, $\eta_p^2 \leq .101$. Results, however, indicated a significant main effect for heel height, $F(2, 33) = 58.396$, $p < .001$, $\eta_p^2 = .780$, and vowel, $F(1, 34) = 313.691$, $p < .001$, $\eta_p^2 = .902$. These results concerning significant main effects was obtained by collapsing data across all other variables. It therefore duplicated findings from research question one and will not be repeated here.

A significant main effect for formant location, $F(1, 34) = 173.092$, $p < .001$, $\eta_p^2 = .836$, indicated that participants, on average, sang with a greater amount of jaw opening ($M = 66.19$ degrees, $SD = 5.10$ degrees) on pitches above the location where F0> F_{1LOWF0}

compared to pitches below the location where F0> F_{1LOWF0} ($M = 61.644$ degrees, $SD = 4.56$ degrees), regardless of heel height or vowel.

Research Question Five: Correlations

Research question five asked if there were any statistically significant relationships between (a) two measures of participant head position (HP 1, HP 2), (b) one measure of participant jaw opening (JO), (c) dB SPL, (d) three heel conditions (0.0 in., 1.5 in., 3.0 in.), (e) two vowel conditions ([ɑ], [i]), (f) 15 pitch conditions (A3-A5), and (g) two behavior conditions (silence, singing). I executed Pearson correlation coefficient tests for the following variables: (a) pitch, (b) vowel, (c) heel height, (d) behavior, (e) head position angle 1, (f) head position angle 2, (g) jaw opening, and (h) dB SPL.

Due to the nature of the small sequential units of the dependent variables in this study, especially for the variable of pitch (e.g., all pitches from A3-A5), I analyzed and conducted correlation coefficient tests in two ways: (a) analysis one, which presented a more general overview of group mean trends, and (b) analysis two, which included all individual participant dependent variable measurements.

Analysis one. For an overview of participant trends, I averaged across all participants for each dependent variable before performing the correlation coefficient test. For example, between pitch and head position angle 1 measurements, I obtained a mean of all participants' head position angle 1 measurements for the pitch A3. I then obtained a mean of all participants' head position angle 1 measurements for the pitch B3, etc. This averaging resulted in one column of across participant mean head position angle 1 measurements for each pitch ($N = 15$) and one column of ordinal numbers coded (1 to 15) to represent each pitch of the scale. Figure 20 represents a plot of this data, which indicated that for the overall analysis of head position angle 1 data, averaged across participants, head position angle 1 measurements increased as pitch ascended. This type of analysis reduced the variance between participants and provided an overall representation of trends across all participants.

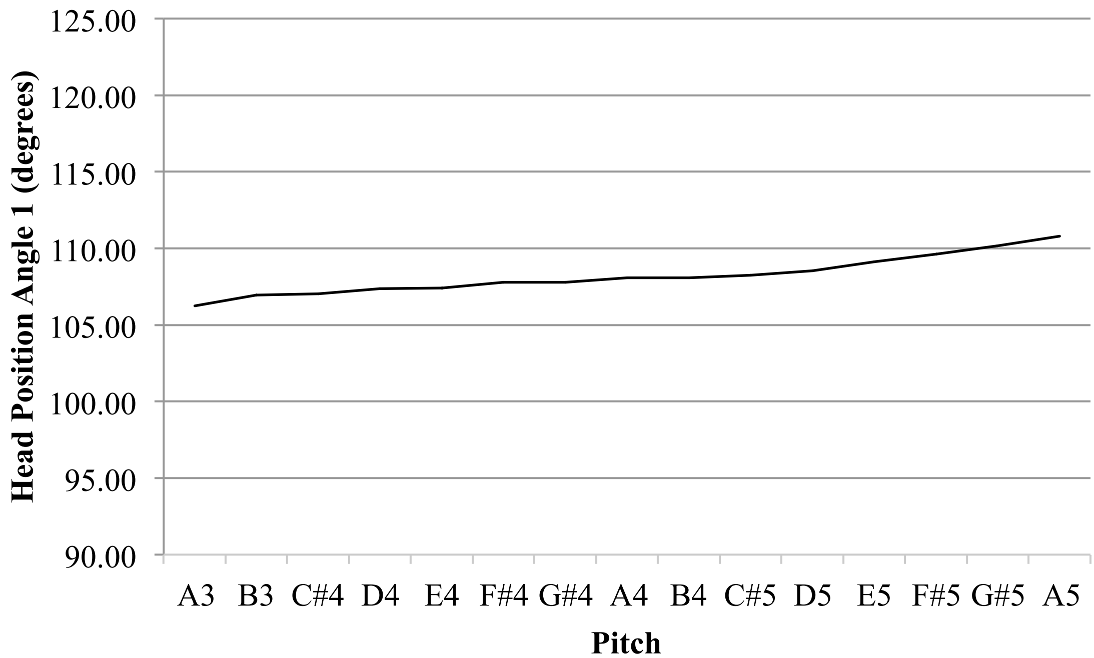

Figure 20. Mean head position angle 1 data for pitches A3-A5: Analysis one.

Table 8 displays the correlation coefficients for this analysis, which indicated significant, very strong, positive correlations across almost every comparison.

Table 8.

Analysis One: Coefficients of Correlation (r) between Pitch, Vowel, Heel Height, Behavior, Head Position, Jaw Opening, and dB SPL Data Averaged Across All Participants

Variable	**Pitch**	**Vowel**	**Heel Height**	**Behavior**	**HP 1**	**HP 2**	**JO**	**dB SPL**
Pitch	[redacted]	[redacted]	[redacted]	[redacted]	.965*	.986*	.932*	.997*
Vowel	[redacted]	[redacted]	[redacted]	[redacted]	1.000*	1.000*	1.000*	1.000*
Heel Height	[redacted]	[redacted]	[redacted]	[redacted]	-.999*	-.985	-.985	.946
Behavior	[redacted]	[redacted]	[redacted]	[redacted]	1.000*	1.000*	1.000*	[redacted]
HP 1	.965*	1.000*	-.999*	1.000*	[redacted]	.930**	.908*	.970**
HP 2	.986*	1.000*	-.985	1.000*	.930**	[redacted]	.895**	.985**
JO	.932*	1.000*	-.985	1.000*	.908*	.895**	[redacted]	.909**
dB SPL	.997*	1.000*	.946	[redacted]	.970**	.985**	.909**	[redacted]

Note. **Correlation significant at the 0.01 level (two-tailed). *Correlation significant at the 0.05 level (two-tailed).

The correlation between dB SPL and heel height, although very strong and positive, was not significant (p = .211). A significant, very strong, negative correlation existed between heel height and head position angle 1 measurements, $r(1) = -.999$, p = .034. Results revealed non-significant, very strong, negative relationships between (a) heel height and head position angle 2 measurements, $r(1) = -.985$, p = .110, and (b) heel height and jaw opening measurements, $r(1) = -.985$, p = .112.

Analysis one collapsed across all participants in order to account for group trends. Therefore, one might expect an almost perfect correlation between some variables, as the data simply represented group mean trends. For the independent variable of pitch, which included 15 small sequential changes, analysis one may be of greater importance. However, for the other independent variables of heel height, vowel, and behavior, analysis one should be interpreted with caution.

Analysis two. For a traditional analysis of the correlation coefficients, I used each unit measurement of the dependent variable from every individual participant. For example, I used each individual participant's head position angle 1 measurement on each pitch (A3-A5). I imported this data into SPSS, which resulted in one column of individual participant head position angle 1 measurements (N = 525, 15 per pitch, per participant) and one column of ordinal numbers coded to match the particular pitch participants sang (N = 525, 35 coded as pitch 1, 35 coded as pitch 2, etc.). SPSS then computed the correlation coefficient to represent the relationship between these two sets of numbers. Figure 21 displays a graph that includes each participant's head position angle 1 measurement. When looking at the relationship between head position angle 1 measurements and pitch in this way, it appeared that although individual participants may have exhibited slight alterations in head position angle 1 measurements between small incremental steps in pitch, an overall trend still appeared. It seemed that participants may not have exhibited a linear trend individually, but instead exhibited a larger increase in this particular dependent variable around the pitch of C#5.

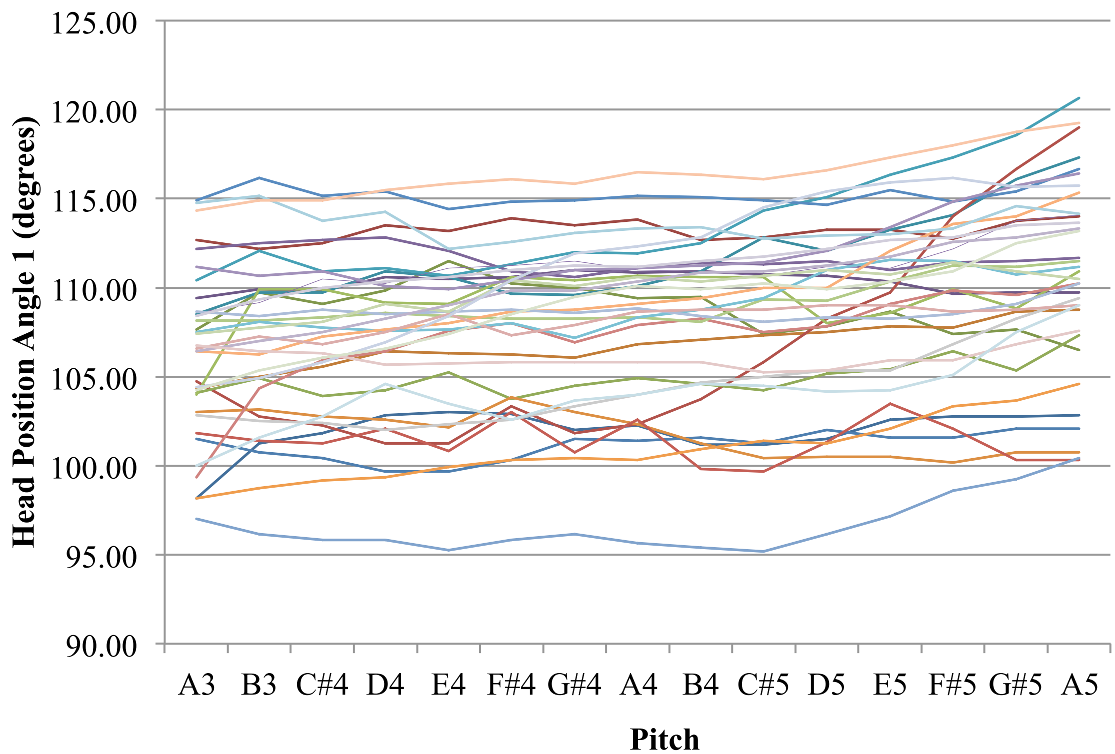

Figure 21. Individual participant head position angle 1 data for pitches A3-A5: Analysis two.

As indicated in Table 9, a significant, very strong, positive correlation existed between pitch and dB SPL, $r(523) = .934$, $p < .001$. As pitch ascended, participants increased amplitude (dB SPL). Significant, strong, positive correlations existed between (a) pitch and jaw opening measurements, $r(523) = .453$, $p < .001$, and (b) behavior and jaw opening measurements, $r(68) = .639$, $p < .001$. As pitch ascended and from silent to singing behavior, jaw opening tended to increase. Results also indicated significant, moderate, positive relationships between (a) jaw opening and head position angle 1 measurements, $r(523) = .349$, $p < .001$ and (b) jaw opening measurements and dB SPL, $r(523) = .327$, $p < .001$. As jaw opening increased, head position angle 1 measurements and dB SPL tended to increase.

Results indicated significant, moderate, negative correlations between (a) jaw opening and vowel, $r(68) = -.340$, $p = .004$ and (b) heel height and head position angle 1 measurements, $r(103) = -.396$, $p < .001$. As the vowel changed from the open vowel [ɑ] to the closed vowel [i], jaw opening tended to decrease. As heel height increased, head position angle 1 measurements tended to decrease. Hereafter, reference to correlation coefficients will refer to data from analysis two, which used each unit measurement of the dependent variable from every individual participant.

Table 9.

Analysis Two: Coefficients of Correlation (r) between Pitch, Vowel, Heel Height, Behavior, Head Position, Jaw Opening, and dB SPL Including All Participants' Individual Unit Measurements

Variable	Pitch	Vowel	Heel Height	Behavior	HP 1	HP 2	JO	dB SPL
Pitch					.239**	.09*	.453**	.934**
Vowel					-.120	-.046	-.340**	-.085
Heel Height					-.396**	-.234*	-.296**	.020
Behavior					.293*	.115	.639**	
HP 1	.239**	-.120	-.396**	.293*		.251**	.349**	.147**
HP 2	.09*	-.046	-.234*	.115	.251**		.053	.059
JO	.453**	-.340**	-.296**	.639**	.349**	.053		.327**
dB SPL	.934**	-.085	.020		.147**	.059	.327**	

Note. **Correlation significant at the 0.01 level (two-tailed). *Correlation significant at the 0.05 level (two-tailed).

Summary

Primary findings included significant main effects for heel height, pitch, vowel, behavior, and formant location conditions on participants' postural and acoustical data. As heel height increased, participants significantly (a) decreased head position angle 1 and angle 2, (b) decreased jaw opening, (c) decreased LTAS mean signal energy, and (d) increased amplitude (dB SPL). As pitch ascended, participants, on average, significantly (a) increased head position angle 1 and angle 2, (b) increased jaw opening, and (c) increased amplitude (dB SPL). When singing the open vowel of [ɑ] compared to the closed vowel of [i], participants significantly (a) increased head position angle 1 and angle 2, (b) increased jaw opening, and (c) increased amplitude (dB SPL). From silent to singing behaviors, participants significantly (a) increased head position angle 1 and angle 2, and (b) increased jaw opening. Participants significantly increased head position angle 1, head position angle 2, and jaw opening when singing pitches above the point where the fundamental frequency (F0) would equal or exceed the first format frequency (F1) of the low pitch of A3.

Data analyses yielded multiple significant interactions between independent variables and indicated significant, moderate to strong, positive relationships between (a) pitch and dB SPL, (b) pitch and jaw opening, (c) jaw opening and behavior, (d) jaw opening and head position angle 1, and (e) jaw opening and dB SPL, and significant, moderate, negative correlations between (a) jaw opening and vowel, and (b) heel height and head position angle 1.

Results also indicated significant, strong, positive correlations between (a) pitch and dB SPL, (b) pitch and jaw opening, and (c) jaw opening and behavior. Significant, moderate, positive correlations occurred between (a) jaw opening and head position angle 1, and (b) jaw opening and dB SPL, with significant, moderate, negative correlations between (a) jaw opening and vowel, and (b) heel height and head position angle 1.

CHAPTER FIVE

Discussion

Results of this study, in the main, appear to underscore interconnection and reciprocity among the postural and acoustical phenomena examined in the sung performances of 35 female singers. Among overarching findings: (a) participants, on the whole, significantly and incrementally decreased head position, jaw opening, and LTAS mean signal energy data as heel height increased; (b) participants, on the whole, significantly increased head position, jaw opening, and dB SPL as pitch ascended; and (c) participants, on the whole, significantly increased head position, jaw opening, and dB SPL on the open front vowel [ɑ] compared to the closed front vowel [i].

Data analyses also show multiple significant interactions and multiple significant associations among the variables of this investigation. There are significant interactions between (a) heel height, pitch, and head position angle 2, (b) pitch, vowel, and jaw opening, (c) heel height, behavior, and jaw opening, (d) vowel, heel height, and LTAS data, (e) pitch, vowel, and dB SPL data, and (f) heel height, vowel, formant location, and head position angle 2. Correlation coefficients exhibit moderate to strong associations between (a) pitch and dB SPL, (b) pitch and jaw opening, (c) jaw opening and behavior, (d) jaw opening and head position angle 1, (e) jaw opening and dB SPL, (f) jaw opening and vowel, and (g) heel height and head position angle 1.

The primary purpose of this study was to assess the effects of heel height on singers' postural and acoustical measurements. Pursuant to that purpose, this investigation also considered the effects of vowel, pitch, behavior (silent, singing), and formant location on postural and acoustical data, along with examination of relationships between and among the variables of the study. Results are limited to the participants, methodology, and procedures of this particular investigation. However, these findings raise numerous matters that merit consideration and further exploration by singers, teachers, and researchers.

Singing is a complex phenomenon. The present study, the third in a line of investigations (cf. Rollings, 2013, 2014a) that consider the contributions of heel height to postural and acoustical measures of female singers, arises from a comprehensive review of research literature. That review suggests a need for investigations of singing that examine simultaneously, rather than separately, the effects of heel height, pitch, vowel, behavior, and formant location on singers' postural and acoustical measurements. Of course, one consequence of a research decision to incorporate numerous independent and dependent variables is a mountain of data.

To explore implications and possible meanings of these data, the following discussion first employs lenses afforded by the independent variables of (a) heel height, (b) vowel, and (c) pitch. It then offers concluding thoughts for vocal pedagogy and vocal pedagogy research. Other suggestions for future research, implications for vocal music education, and consideration of the limitations of this study will be addressed throughout the chapter.

It is important at the outset to reiterate that the results of this study (a) reflect data averaged across two trials by each participant and (b) represent whole group mean data used for statistical analyses and description. In other words, given the large scope of this study, findings reference overall group behavior. Subsequent studies of smaller scope may well wish to address variations, trends, and nuances among individual singers that could be informative.

Heel Height

This study, following Bendix et al. (1984), examines heel height by means of wooden boards that simulate three heel heights (0.0 in., 1.5 in., 3.0 in.). The primary advantages of this method are its low cost and control of possible confounding variables due to differences in shoe construction, including slight variations in heel height. It could be argued, however, that simulated heel height produces an artificial, rather than naturalistic, condition. Singers in performance, after all, wear shoes; they do not typically stand on boards. In this sense, use of simulated heel heights may constitute a limitation of this study.

Moreover, the present study addresses only changes in vertical heel height. Future investigations might employ ways to simulate various modes of shoe heel conditions, such as possible differences between wedge heels and stiletto heels.

Head position. Only two studies to date (Iunes et al., 2008; Opila et al., 1988) address possible effects of heel height on head position, finding that the extent of previous experience in wearing high heeled shoes may affect the degree of change in participants' head position. These investigations, however, occur in non- singing contexts. One contribution of the present study is its focus on female singers in both performance and silent conditions. The finding that participants on the whole incrementally lower head position as heel height increases while singing appears to confirm results from Rollings (2013, 2014a). The finding that participants also lower head position incrementally as heel height increases while standing silently may have implications for heel height research with participants from the general population.

Correlation data from this investigation suggest a significant, moderate, negative relationship between heel height and head position angle 1 measurements. It appears that as heel height increases, participants simultaneously exhibit a lowering of the head. As previous research (e.g., Muto & Kanazawa, 1994; Tong, Sakakibara, Hix, & Suetsugu, 2000, Shelton & Bosma, 1962) in sleep apnea and orthodontics indicates, alterations of head position can elicit changes in the dimensions of the vocal tract. Thus, modifications of the vocal tract due to heel height adjustments and changes in head position could be of interest to singers and vocal music teachers. Subsequent studies might well explore the pedagogical implications of this possibility, in addition to physiological and acoustical implications.

One possible explanation for decreased head position measurements due to heel height could be the anatomical and physiological function of the erector spinae muscle group. When the muscles of the erector spinae muscle group contract, the head moves posteriorly and the chest moves anteriorly on the horizontal plane (Erector Spinae, n.d.). A few studies (e.g., Lee et al., 2001) suggest that participants exhibit increased activity in the erector spinae muscle group when wearing high heels in order to compensate for the change in mean center of gravity, the sensation of falling forward, and the decreased degree of lumbar lordosis. It is possible that participants in the present study exhibit a posterior movement in head position (decrease in head position angle 2 measurements) as heel height increases because of a contraction of the erector spinae.

Opila et al. (1988) suggest that an increase in the activity of the erector spinae muscle group corresponds to an increase in the muscle activity of the lower abdominal muscles. Singers in prior studies (e.g., Rollings, 2013, 2014a) comment they perceive a decline in breath support when singing in high heels. Two studies with non-singing participants (Mathews & Wooten, 1963; Ebbeling et al., 1994) suggest that female participants use a significantly greater amount of oxygen and exhibit an increase in heart rate while walking in high heel shoes. Future research may examine in depth the implications of heel height for a singer's lumbar anatomy and breathing mechanism.

Of particular interest in the context of the present study, however, are the simultaneous findings that (a) while heel height apparently contributes to lowered head position in both silent and singing conditions, which suggests that simply wearing high heels may result in decreased head position; (b) participants, on the whole, significantly raise head position when transitioning from silent to singing conditions, likely in order to open the jaw for singing as pitch ascends. A significant, strong, positive correlation between jaw opening and behavior and a significant, moderate, positive relationship between jaw opening and head position angle 1 measurements appear also to support the idea that singers may increase head position between silent and singing conditions in order to open the jaw.

Jaw opening. Numerous studies in sleep apnea and orthodontic research (e.g., Muto & Kanazawa, 1994; Goldstein et al., 1984, Eriksson et al., 1998; Zafar et al., 2000) document that jaw opening and head position tend to move concomitantly. The present investigation moves that understanding a step further in its finding that heel height may also play a role in altering jaw opening. Specifically, participants in this study appear to decrease jaw opening as heel height increases.

Arguably, the singers in this study display a smaller jaw opening due to the downcast head posture prompted by increases in heel height. If, then, heel height instigates a decrease in head position angle 1 measurements (inferior movement of the head), a female singer might find that it requires more effort to open the jaw to sing in high-heeled shoes. This matter warrants continued research. Future research may also include a measurement angle of the Chin-Tr-Sternum to explore further the relationship between head position and jaw opening.

Voice research aims to control for factors outside of those being tested in a particular study. This study demonstrates the importance of considering head position when conducting voice research. For example, choral research may test participants singing in various rooms or with various conductor gestures while using choir folders. One might speculate that if some choral members memorize the piece over the length of the study, they might look up from the score, thereby elevating their head position and possibly altering their acoustical output. Similarly, if the height of the conductor differs between conditions, participants might raise or lower their head positions, which could again affect acoustical output. These variables that may occur during the scope of a research study warrant close attention.

Voice research to date typically uses MRI to assess postural changes in jaw opening over a range of pitches. Data from this study suggest a positive relationship between head position and jaw opening. Future research may investigate whether having participants in a supine position where head movement may be limited for data collection could disguise the true degree of jaw opening alterations relative to pitch or vowel that standing participants may exhibit. Similarly, if singer head position studies limit the ability of participants to open the jaw (e.g., by specifying humming), one might speculate that alterations in head position may be attenuated.

First formant frequency. The formant frequency data of this study serve only to determine and describe the approximate pitch at which the fundamental frequency would equal or exceed the first formant frequency. Thus, I did not test for significant differences in formant frequency related to heel height, pitch, or vowel. However, the descriptive results indicate that for these participants on the whole the first formant frequency of the low pitch of A3 slightly decreased as heel height increased. Due to the interconnectivity of head position and jaw opening, this decline in the first formant frequency most likely results from the lowering of head position due to heel height, which may consequently result in a more closed jaw. This finding supports the conclusions of some former studies, which indicate that a more closed jaw position corresponds with a decrease in the first formant frequency (e.g., Lindblom & Sundberg, 1971). Because the data from this study indicate that jaw opening and head position seem to vary together, future research may wish to examine the potential effects of head position on formant frequencies, especially with regard to the first formant.

Formant tuning and dB SPL. Many studies report that female singers use jaw opening to increase the first formant frequency to aid in formant tuning (e.g., Sundberg, 1975; Sundberg & Skoog, 1997). If an increase in heel height predisposes a singer to exhibit a lower head position and more closed jaw position, it would make sense that heel height could instigate problems in formant tuning for female singers on high pitches. In this case, one might expect to see a loss of amplitude on high pitches, because it is commonly understood that formant tuning boosts amplitude (Sundberg, 1987). However, the dB SPL data from this study do not indicate steady decreases in singer amplitude even with steady decreases in jaw opening and head position as heel height increases. Therefore, future studies could consider the possible compensation techniques singers may employ in order to formant tune with a decreased jaw opening. Future studies might also address whether vocal experience contributes to participant acoustical responses to alterations in heel height.

LTAS. A few previous studies (e.g., Rollings, 2013, 2014a) explore the effects of heel height on LTAS data acquired from female singers, with mixed results. Some participants increase mean signal energy as heel height increases, while others behave in the opposite way. Rollings (2012, 2014b) finds, in particular, that as head position angle 1 increases, LTAS mean signal energy increases. Similarly, as head position angle 1 decreases, LTAS mean signal energy decreases. The LTAS data from this study agree with those findings, as participants, on the whole, sang with the least mean spectral energy in the 3.0 in. heel condition, which also exhibited the lowest head position angle 1 measurements.

However, in the present study, the interaction between vowel, heel height, and LTAS data indicates that vowel combined with heel height may provide a more complete account for the variance in LTAS data. Based on this interaction, it seems that, on the vowel [ɑ], participants exhibit more variance in mean LTAS signal data than on the vowel [i]. This difference could be due to the nature of the [ɑ] vowel, which may require singers to exhibit more jaw opening than on the vowel [i]. The [i] vowel, on the other hand, requires more action of the tongue and less movement of the jaw. Therefore, the [ɑ] vowel may elicit a greater variance in jaw opening due to increases in heel height, which may lead to a greater variance in LTAS data on the vowel [ɑ] compared to the vowel [i].

The fact that participants in this study, as a group, significantly alter LTAS data across heel height conditions merits reflection. Differences in LTAS spectral energy can indicate alterations in vocal timbre. Although LTAS results from this study do not indicate changes in mean signal energy or individual harmonics sufficient to constitute a 1 dB just noticeable difference (c.f. Howard & Angus, 2001), every harmonic of the spectrum (0 – 10 kHz) decreased when participants sang in 3.0 in. heel conditions compared to 0.0 in. heel conditions. Future research is needed to determine if and to what extent smaller deviations of each harmonic in a complex sound might affect listener perceptions of vocal timbre.

Vowel

Previous research (e.g., Austin, 2007) indicates that singers exhibit a larger jaw opening on more open vowels compared to more closed vowels. The present study, however, also looks at potential alterations in head position based on changes in vowel. It finds that when comparing the vowel [ɑ] to the vowel [i], participants (a) increase head position (HP 1, HP 2) and jaw opening, and also (b) increase dB SPL.

Additionally, data from this study show a significant, negative, moderate correlation between vowel and jaw opening. This finding indicates that as the openness of one vowel changes toward a more closed second vowel (e.g., [ɑ] versus [i]), participants tend to exhibit less jaw opening. Although some teachers may advise students to keep the jaw opening consistent across all vowels, data from this study indicate that, on the whole, participants do not keep jaw opening consistent when singing the vowel [ɑ] compared to the vowel [i]. Further research may examine if it is indeed possible to keep the jaw opening consistent across multiple vowel types.

An interaction between jaw opening, pitch, and vowel indicates that participants exhibit a similar jaw opening regardless of vowel on the high pitch of A5. This factor appears to support the idea that singers modify a vowel as pitch ascends, which results in a similar jaw opening on high pitches, regardless of vowel. It is unclear whether participants in this study consciously modify the vowels to have a similar jaw opening on the high pitch of A5 or subconsciously alter the vowel in order to formant tune and boost dB SPL. Subsequent studies might well address this matter.

An interaction between pitch, vowel, and dB SPL also suggests that vowel quality may be related to amplitude relative to low, medium, and high pitches. On the low pitch of A3, participants seem to exhibit a larger degree of mean variance in amplitude between vowels. This variance decreases as pitch ascends. As participants sing the high pitch of A5, moreover, the mean difference in amplitude between [ɑ] and [i] decreases. One explanation for an increase in amplitude on the [ɑ] vowel might be related to the significant, moderate, positive correlation found between jaw opening and dB SPL. It appears that as jaw opening increases, dB SPL increases. If singers exhibit a more open jaw position on the vowel [ɑ] compared to the vowel [i], it would make sense that given the relationship between jaw opening and dB SPL, singers might exhibit an increase in amplitude while singing more open vowels. If singers exhibit more amplitude with a greater amount of jaw opening, future research may investigate whether having singers consciously increase jaw opening on the more closed vowels [i] and [u] would assist with projection, especially on pitches in the low and middle voice.

Overall, it appears that head position and jaw opening may elicit changes in singer amplitude on sung pitches. Because the present study analyzed only two vowels, future studies should also consider whether postural and acoustical differences exist among a wider range of vowel types.

Pitch

The results of this study regarding alterations in head position and jaw opening with changes in pitch confirm the findings of previous research (e.g., Curry, 1937; Austin, 2007; Honda et al., 1999; Johnson & Skinner, 2009; Miller et al., 2012a), which suggest that participants increase cervical lordosis (neck curvature) or head position as pitch ascends. Similarly, Scotto Di Carlo (1998) explains that professional singers, who spend considerable time practicing and performing, may exhibit cervical spine abnormalities because the jaw opening needed to sing higher pitches may require singers to adjust the cervical spine. By contrast, the general population rarely needs to open the jaw to such an extreme, which could explain why Scotto Di Carlo found no cervical spine abnormalities among the non-singing participants in her study.

As might be expected from the perspective of pitch-amplitude effect, the strongest, positive correlation of this study suggests that as pitch ascends, singers increase amplitude (dB SPL). Another strong, positive correlation suggests a linear relationship between pitch and jaw opening. By combining this information, one might speculate that singers use jaw opening as a means of formant tuning, which boosts amplitude at higher frequencies. That jaw opening also significantly, moderately, and positively correlates with head position angle 1 measurements, indicates that singers may use a combination of head position and jaw opening to increase dB SPL as pitch ascends.

Vocal pedagogy literature predominantly advises singers not to increase head position as pitch ascends (e.g., Miller, 2004). However, the data from this study and others (e.g., Austin, 2007; Miller et al., 2012a) indicate that singing higher pitches may require a singer to increase or elevate head position in order to accommodate jaw opening, especially in the case of female voice formant tuning. Voice professionals may wish to consider that a slightly elevated head position may be conducive to efficient singing, the ability to efficiently open the jaw, and perhaps the ability to successfully formant tune. Austin (2012), for example, advises singers to lift the head slightly when singing. However, more research in this area is needed. Future studies may also explore differences in head position and jaw opening across vocal styles and vocal experience levels.

Concluding Implications for Voice Pedagogy and Voice Pedagogy Research

Data from this controlled study of 35 female singers suggest that elevated heel height can matter physiologically and acoustically. Heel height accounts for (a) 93.0% of the variation in head position angle 1 measurements, (b) 33.0% of the variation in head position angle 2 measurements when combined with the independent variable of pitch, and (c) 67.7% of the variance in jaw opening. Thus, decisions about whether or not to wear shoes with high heels may not be solely decisions about appearance and costuming. Singers and voice teachers should be aware of the nuances in vocal production that may occur with raised heel heights, specifically the capacity of raised heels to initiate changes in head position and jaw opening, which, in turn, could occasion changes in the dimension of the vocal tract.

Future studies might well explore the extent to which specific pedagogical protocols might help singers best accommodate singing in high-heeled shoes should they be a necessity for particular roles or occasions. Other studies should investigate whether singers performing on raked stages might exhibit effects similar to those of heel height because raked stages elevate the rear portion of the foot.

Male singers might be required to wear shoe lifts in order to be taller than the female singers or to alter their overall look. Thus, it would be interesting to replicate this study with male singers.

Costume designers typically choose the shoes singers will wear in an operatic or musical theatre performances based on the style period dictated by a stage director. One line of research may investigate how these decisions are made and what input singers may have in the process.

Rossi (1993) comments that heel height particularly affects the male perception of a woman. Therefore, it may be impractical to advocate lower heel heights for all auditions and performances due to the perceptions of the auditors. Future research may examine casting trends, along with the perceptions of adjudicators and singers, when vocalists wear different types of shoes.

Female singers make choices each day about what outfit to wear in general or while singing. Although choice of shoes may not make or break a vocal performance, it may behoove singers and voice teachers to become acquainted with the developing body of empirical research about the potential effects of heel height on posture and vocal sound so that they may make informed decisions.

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Appendix A

Complete List of Research and Sub-Research Questions

Note: The research questions listed in Chapter One appear in bold print.

The purpose of this study was (a) to determine the effects, if any, of three simulated heel height conditions (0.0 in., 1.5 in., 3.0 in.) on postural (head position, jaw opening) and acoustical (LTAS, dB SPL) measures of university female voice majors (*N* = 35) in two conditions (silence, singing sustained [ɑ] and [i] vowels on each pitch of a two-octave A-major scale [A3-A5]), and then to (b) assess selected relationships between heel height behavior conditions, postural data, and acoustical data.

1. **Are there statistically significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (b) two behavior conditions (silent, singing), (c) two vowel conditions ([ɑ], [i]), and (d) three pitch conditions (low [A3], medium [A4], high [A5])?**
    a. Are there statistically significant differences among participant head position angle 1 measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in.,3.0 in.), (b) two vowel conditions ([ɑ], [i]), and (c) three pitch conditions (low [A3], medium [A4], high [A5])?
    b. Are there statistically significant differences among participant head position angle 2 measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (b) two vowel conditions ([ɑ], [i]), and (c) three pitch conditions (low [A3], medium [A4], high [A5])?
    c. Are there statistically significant differences among participant jaw opening measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (b) two vowel conditions ([ɑ], [i]), and (c) three pitch conditions (low [A3], medium [A4], high [A5])?
    d. Are there statistically significant differences among participant head position angle 1 measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), and (b) two behavior conditions (silent, singing)?
    e. Are there statistically significant differences among participant head position angle 2 measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), and (b) two behavior conditions (silent, singing)?
    f. Are there statistically significant differences among participant head position jaw opening measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), and (b) two behavior conditions (silent, singing)?

2. **Are there statistically significant differences among LTAS data (0 – 10 kHz) acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), and (b) two vowel conditions ([ɑ], [i])?**
3. **Are there statistically significant differences among dB SPL measurements acquired from (a) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), two vowel conditions ([ɑ], [i]), and (c) three pitch conditions (low [A3], medium [A4], high [A5])?**
4. **Are there statistically significant differences among measures of head position (HP 1, HP 2) and jaw opening (JO) acquired from (a) two vowel conditions ([ɑ], [i]) and (b) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), after disaggregating and averaging data for each dependent variable into levels of $\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0})?**
   a. Are there statistically significant differences among head position angle 1 measurements (HP 1) acquired from (a) two vowel conditions ([ɑ], [i]) and (b) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), after disaggregating and averaging data for each dependent variable into levels of $\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0})?
   b. Are there statistically significant differences among head position angle 2 measurements (HP 2) acquired from (a) two vowel conditions ([ɑ], [i]) and (b) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), after disaggregating and averaging data for each dependent variable into levels of $\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0})?
   c. Are there statistically significant differences among jaw opening measurements (JO acquired from (a) two vowel conditions ([ɑ], [i]) and (b) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), after disaggregating and averaging data for each dependent variable into levels of $\bar{X}_{PITCH>F1LOWF0}$ (pitches higher than the location of F_{1LowF0}) and $\bar{Y}_{PITCH<F1LOWF0}$ (pitches lower than the location of F_{1LowF0})?
5. **Are there statistically significant relationships between (a) two measures of participant head position (HP 1, HP 2), (b) one measure of participant jaw opening (JO), (c) dB SPL, (d) three heel height conditions (0.0 in., 1.5 in., 3.0 in.), (e) two vowel conditions ([ɑ], [i]), (f) 15 pitch conditions (A3-A5), and (g) two behavior conditions (silent, singing)?**
   a. Is there a statistically significant correlation between pitch (A3-A5) and head position angle 1 measurements (HP 1)?
   b. Is there a statistically significant correlation between pitch (A3-A5) and head position angle 2 measurements (HP 2)?
   c. Is there a statistically significant correlation between pitch (A3-A5) and jaw opening measurements (JO)?
   d. Is there a statistically significant correlation between pitch (A3-A5) and dB SPL measurements?

e. Is there a statistically significant correlation between vowel ([ɑ], [i]) and head position angle 1 measurements (HP 1)?
f. Is there a statistically significant correlation between vowel ([ɑ], [i]) and head position angle 2 measurements (HP 2)?
g. Is there a statistically significant correlation between vowel ([ɑ], [i]) and jaw opening measurements (JO)?
h. Is there a statistically significant correlation between vowel ([ɑ], [i]) and dB SPL measurements?
i. Is there a statistically significant correlation between heel height (0.0 in., 1.5 in., 3.0 in.) and head position angle 1 measurements (HP 1)?
j. Is there a statistically significant correlation between heel height (0.0 in., 1.5 in., 3.0 in.) and head position angle 2 measurements (HP 2)?
k. Is there a statistically significant correlation between heel height (0.0 in., 1.5 in., 3.0 in.) and jaw opening measurements (JO)?
l. Is there a statistically significant correlation between heel height (0.0 in., 1.5 in., 3.0 in.) and dB SPL measurements?
m. Is there a statistically significant correlation between behavior (silent, singing) and head position angle 1 measurements (HP 1)?
n. Is there a statistically significant correlation between behavior (silent, singing) and head position angle 2 measurements (HP 2)?
o. Is there a statistically significant correlation between behavior (silent, singing) and jaw opening measurements (JO)?
p. Is there a statistically significant correlation between head position angle 1 measurements (HP 1) and head position angle 2 measurements (HP 2)?
q. Is there a statistically significant correlation between head position angle 1 measurements (HP 1) and jaw opening measurements (JO)?
r. Is there a statistically significant correlation between head position angle 1 measurements (HP 1) and dB SPL measurements?
s. Is there a statistically significant correlation between head position angle 2 measurements (HP 2) and jaw opening measurements (JO)?
t. Is there a statistically significant correlation between head position angle 2 measurements (HP 2) and dB SPL measurements?
u. Is there a statistically significant correlation between jaw opening measurements (JO) and dB SPL measurements?

Appendix B

Human Subjects Approval Letter

THE UNIVERSITY OF KANSAS
Research

APPROVAL OF PROTOCOL

March 20, 2015

Amelia Rollings
arollings@ku.edu

Dear Amelia Rollings:

On 3/20/2015, the IRB reviewed the following submission:

Type of Review:	Initial Study
Title of Study:	Head Over Heels: The Effects of Three Heel Heights on Postural and Acoustical Measures of University Female Voice Majors, and Measured Relationships Between Heel Height, Pitch, Vowel, Behavior, Head Position, Jaw Opening, and dB SPL
Investigator:	Amelia Rollings
IRB ID:	STUDY00002328
Funding:	None
Grant ID:	None
Documents Reviewed:	• Consent Form, • NEWHeadOverHeelInitalForm.pdf, • NEWRecruitingEmail.docx, • Survey, • DeBriefing Statement,

The IRB approved the submission from 3/20/2015 to 3/19/2016.

1. Before 3/19/2016 submit a Continuing Review request and required attachments to request continuing approval or closure.
2. Any significant change to the protocol requires a modification approval prior to altering the project.
3. Notify HSCL about any new investigators not named in original application. Note that new investigators must take the online tutorial at https://rgs.drupal.ku.edu/human_subjects_compliance_training.
4. Any injury to a subject because of the research procedure must be reported immediately.
5. When signed consent documents are required, the primary investigator must retain the signed consent documents for at least three years past completion of the research activity.

If continuing review approval is not granted before the expiration date of 3/19/2016 approval of this protocol expires on that date.

Please note university data security and handling requirements for your project:
https://documents.ku.edu/policies/IT/DataClassificationandHandlingProceduresGuide.htm

You must use the final, watermarked version of the consent form, available under the "Documents" tab in eCompliance.

Sincerely,

Stephanie Dyson Elms, MPA
IRB Administrator, KU Lawrence Campus

Appendix C

Approved Participant Consent Form

Consent and Authorization Form (Singer Participant)
HSCL #: STUDY00002328
Approval Period: 3/20/2015 – 3/19/2016

TITLE
Acoustical Changes in Singers

INTRODUCTION
The Department of Music Education and Music Therapy at the University of Kansas supports the practice of protection for human subjects participating in research. The following information is provided for you to decide whether you wish to participate in the present study. You may refuse to sign this form and not participate in this study. You should be aware that even if you agree to participate, you are free to withdraw at any time. If you do withdraw from this study, it will not affect your relationship with this unit, the services it may provide to you, or the University of Kansas.

PURPOSE OF THE STUDY
This investigation studies acoustical changes in singers.

PROCEDURES
Please come to the study with your hair pulled back away from your face and neck. Please bring a pair of clean socks. You will choose a pair of ballet slippers (sizes 6-10, including half sizes) to wear on top of your socks for the duration of the study. Please be prepared to sing two-octave, ascending A-major scales (A3-A5) on the vowels [a] and [i]. You will sustain each pitch of the scale on the selected vowel for 3 seconds each. You will complete the singing task while standing on three different foundational boards. Please come to the research room already warmed up as if you were going to perform in an audition or recital. If you are feeling sick or vocally unhealthy, please let the researcher know before coming to the research room so that a different day for data collection can be arranged.

You will be marked with easily removable stickers on areas of your face and neck. A head microphone will be placed on your face and adhered with tape that is easily removable. You will be asked to perform the two-octave scales on each vowel ([a], [i]), twice in each foundational board condition, for a total of twelve times. You will complete a brief survey before exiting the research room.

You will be video and audio recorded while you sing. These recordings are required in order for you to participate in this study. By signing this consent form, you are agreeing to be video and audio recorded. You have the option of not being recorded or stopping the audio/visual recordings at any time during the study without any consequences, however please understand that this will exclude you from the study. Video and audio recordings will be used by the researchers for analysis and will be used in a perceptual study by a panel of voice teacher and coach listeners. There will be no transcribing of the video and audio recordings, only the analysis listed above. Your name will not be attached to any recordings. Video and audio recordings will be stored on a password-protected hard drive in a locked office. Recordings will be destroyed after a period of three years. You will be assigned a pseudonym which will be used in any file names, correspondence or resulting information unless you give written permission otherwise.

You will have an option on the survey of whether or not you consent to being contacted after the study for debriefing. If you select "yes" and confirm that you consent, you will receive an email on March 29, 2015 that details the full extent and description of the study. You will be given the opportunity to withdraw your data at this point and you will be asked to confirm you received the email. If you select "no," you will be given a debriefing document before exiting the research room. All email addresses and email correspondence will be fully deleted from the researcher's computer on April 1, 2015.

Your total time commitment for this study should be no more than 30 minutes.

RISKS
No participant risks are anticipated.

BENEFITS
The benefits of this study will be practical knowledge for professional singers and voice professionals in the field.

PAYMENT TO PARTICIPANTS
Participants will not be paid.

PARTICIPANT CONFIDENTIALITY
Your name will not be associated in any publication or presentation with the information collected about you or with the research findings from this study. Instead, the researcher(s) will use a pseudonym rather than your name. Your identifiable information will not be shared unless (a) it is required by law or university policy, or (b) you give written permission.

Permission granted on this date to use and disclose your information remains in effect indefinitely. By signing this form you give permission for the use and disclosure of your information for purposes of this study at any time in the future.

REFUSAL TO SIGN CONSENT AND AUTHORIZATION
You are not required to sign this Consent and Authorization form and you may refuse to do so without affecting your right to any services you are receiving or may receive from the University of Kansas or to participate in any programs or events of the University of Kansas. However, if you refuse to sign, you cannot participate in this study.

CANCELLING THIS CONSENT AND AUTHORIZATION
You may withdraw your consent to participate in this study at any time. You also have the right to cancel your permission to use and disclose further information collected about you, in writing, at any time, by sending your written request to: Amelia Rollings, 576 Murphy Hall, 1530 Naismith Dr., The University of Kansas, Lawrence, KS 66044.
If you cancel permission to use your information, the researchers will stop collecting additional information about you. However, the research team may use and disclose information that was gathered before they received your cancellation, as described above.

QUESTIONS ABOUT PARTICIPATION
Questions about procedures should be directed to the researcher(s) listed at the end of this consent form.

PARTICIPANT CERTIFICATION
I have read this Consent and Authorization form. I have had the opportunity to ask, and I have received answers to, any questions I had regarding the study. I understand that if I have any additional questions about my rights as a research participant, I may call (785) 864-7429 or (785) 864-7385, write the Human Subjects Committee Lawrence Campus (HSCL), University of Kansas, 2385 Irving Hill Road, Lawrence, Kansas 66045-7568, or email irb@ku.edu.

I agree to take part in this study as a research participant. By my signature I affirm that I am at least 18 years old and that I have received a copy of this Consent and Authorization form.

_______________________________ _____________________
Type/Print Participant's Name Date

____
Participant's Signature

Researcher Contact Information:

Amelia Rollings
Principal Investigator
Music Education and Music Therapy
576 Murphy Hall
University of Kansas
Lawrence, KS 66044
803-348-8119

Dr. James Daugherty
Faculty Supervisor
Music Education and Music Therapy
576 Murphy Hall
University of Kansas
Lawrence, KS 66044

Appendix D

Participant Demographic Survey

<u>Singer Participant Survey</u>:

Contact and Personal Information:
Participant Number: ____
Age:______
Degree: B. A. B. M. M. M. M.A. D.M.A.
Major:____
Primary
Instrument:____
Voice type: ___soprano ___mezzo soprano ___contralto ___I don't know

Musical Experience:
Years of vocal study (one on one voice training): _______

I was feeling vocally healthy when I began the performance today.
Strongly Disagree Disagree Neither Agree nor Disagree Agree Strongly Agree

I was feeling physically healthy when I began the performance today.
Strongly Disagree Disagree Neither Agree nor Disagree Agree Strongly Agree

Can the researcher send you a debriefing email on March 29, 2015? Yes No

Appendix E

Praat Script for Extraction of dB SPL Data

```
table = do ("Create Table with column names...", "data", 420, "filename p1 p2 p3 p4 p5 p6 p7 p8 p9 p10
p11 p12 p13 p14 p15")
row =1
directory$ = "C:\Users\a612r692\Desktop\Audio_Recordings\"
writeInfoLine ("Reading directory ",directory$)
strings = do ("Create Strings as file list...", "fileList", directory$ +"*.wav")
numberOfFiles = do ("Get number of strings")
appendInfoLine ("Number of files is ", numberOfFiles)

for ifile to numberOfFiles
   select strings
   fileName$ = do$ ("Get string...", ifile)
   appendInfoLine (fileName$)
   snd = do ("Read from file...",directory$+fileName$)
   #appendInfoLine ("soundfile is number: ",snd)
   #selectObject ("Sound "+fileName$ -".wav")
   grid = do ("To TextGrid (silences)...", 100, 0, -45, 0.1, 0.1, "silent", "sounding")
   plus snd
   do ("Extract intervals where...", 1, "no", "is equal to", "sounding")
   do ("Extract part...", 1.0, 1.2, "rectangular", 1, "no")
   #from 1.4 to 1.6 seconds extracted

   # get all intensities and put them into the table
   n = numberOfSelected ("Sound")
   for i to n
      sound'i' = selected ("Sound", i)
   endfor
   select table
   do ("Set string value...", row, "filename", fileName$)
   for z to n
      select sound'z'
      dB = do ("Get intensity (dB)")
      select table
      do ("Set numeric value...", row, "p'z'", dB)
   endfor

   #increment row in table
   row = row+1

   select all
   minus Strings fileList
   minus Table data
   Remove
endfor

  #write out the table to file
select table
do ("Save as comma-separated file...", "C:\Users\a612r692\Desktop\heelsIntensity.csv")
```